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5030-345, Vol. I, Rev. A  
Electric & Hybrid Vehicle System  
Research & Development Project

# Assessment of the Potential of Hybrid Vehicles

## Summary

F. T. Surber, et al.

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Prepared for  
U.S. Department of Energy  
Through an agreement with  
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by  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

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## PREFACE

In 1976, Congress passed the Electric and Hybrid Vehicle (EHV) Research, Development, and Demonstration Act of 1976, Public Law 94-413, later amended by Public Law 95-238. The Department of Energy is conducting an EHV development program in compliance with that Law. The EHV System Research and Development Project, one element of this Program, is being conducted by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology through an agreement with the National Aeronautics and Space Administration. This report presents the results of the investigations conducted under the Hybrid Vehicle Potential Assessment Task which is a part of the EHV Systems R&D Project.

Early results of this study were used as the technical basis for the Near Term Hybrid Vehicle Development Program now being carried out by the JPL Electric and Hybrid Vehicle System Research and Development Project.

## ABSTRACT

The purpose of this study was to assess the potential of hybrid vehicles as a replacement of the conventional gasoline or diesel fueled internal combustion engine (ICE) vehicle within the next 20 to 30 years. In particular, the primary purpose of this study was to determine if there are hybrid vehicle designs and applications which are technically and economically viable and offer reductions in petroleum usage large enough to warrant major expenditures of R&D funds. A secondary purpose was to identify critical technical areas where R&D can be most usefully concentrated.

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# Volumes Comprising the Hybrid Vehicle Potential Assessment

Report No.	Subject	Author(s)
5030-345, Vol. I*	Summary	F. T. Surber et al.
5030-345, Vol. II	Mission Analysis	F. T. Surber G. K. Deshpande
5030-345, Vol. III	Parallel Systems	S. P. DeGrey
5030-345, Vol. IV	Series Systems	Z. Popinski
5030-345, Vol. V	Flywheel Systems	S. G. Liddle
5030-345, Vol. VI	Cost Analysis	K. S. Hardy
5030-345, Vol. VII	Hybrid Vehicle Review	K. O. Leschly
5030-345, Vol. VIII	Scenario Generation	K. O. Leschly
5030-345, Vol. IX	Power Train Summary, Component Descriptions, HYVEC Vehicle Simulator	S. G. Liddle S. P. DeGrey
5030-345, Vol. X	Electric and Hybrid Vehicle Cost Handbook	R. C. Heft S. C. Heller

\* Same as this report

## CONTENTS

I.	EXECUTIVE SUMMARY -----	1-1
A.	INTRODUCTION -----	1-1
B.	CONCLUSIONS -----	1-1
C.	STUDY SETTING -----	1-2
D.	WORKING QUESTIONS -----	1-3
E.	STUDY ASSUMPTIONS -----	1-7
II.	APPROACH -----	2-1
A.	OBJECTIVES AND SCOPE -----	2-1
B.	APPROACH -----	2-2
C.	CONCEPTS -----	2-5
1.	Equivalent Mission Performance Vehicles -----	2-5
2.	Hybrid Vehicle Break-Even Gasoline Price -----	2-6
3.	Vehicle Replacement -----	2-6
4.	Petroleum Displacement -----	2-6
III.	HYBRID VEHICLE REVIEW -----	3-1
A.	GENERAL FINDINGS -----	3-1
1.	Fuel -----	3-2
2.	Storage -----	3-2
3.	Operating Modes -----	3-2
4.	Power Plants -----	3-4
5.	Hybrid Vehicle Performance -----	3-4
6.	Power Train Schemes -----	3-5

IV.	MISSION ANALYSIS -----	4-1
A.	GENERAL FINDINGS -----	4-2
B.	MISSION SELECTION -----	4-2
C.	TRANSPORTATION REQUIREMENTS -----	4-3
1.	Trip Purposes and Payloads -----	4-3
2.	Driving Cycles -----	4-5
3.	Travel Patterns -----	4-5
D.	VEHICLE DESIGN REQUIREMENTS -----	4-5
1.	Sustained Speed -----	4-5
2.	Acceleration -----	4-5
3.	Gradeability -----	4-8
4.	Basic Vehicle Characteristics -----	4-8
V.	POWER TRAIN ANALYSIS -----	5-1
A.	GENERAL FINDINGS -----	5-1
B.	SELECTION PROCESS -----	5-2
C.	PARALLEL HYBRIDS -----	5-4
1.	Fuel Economy -----	5-5
2.	Battery Specific Energy and Specific Power -----	5-5
3.	Design Considerations -----	5-6
4.	Configurations -----	5-7
5.	Control Strategies -----	5-8
VI.	COST ANALYSIS -----	6-1
A.	GENERAL FINDINGS -----	6-1
B.	COSTING METHODOLOGY -----	6-4
1.	Vehicle Design -----	6-4



2.	Battery Life -----	6-4
3.	EHV Cost Handbook -----	6-5
C.	FUEL DISPLACEMENT TRADE-OFFS -----	6-6
1.	Acquisition Cost Ratio vs Fuel Displacement -----	6-6
2.	Operating Cost Ratio vs Fuel Displacement -----	6-8
3.	Life Cycle Cost vs Fuel Displacement -----	6-9
4.	Break-Even Gasoline Price vs Fuel Displacement -----	6-10
5.	Battery Cost Requirements vs Fuel Displacement -----	6-12
VII.	HYBRID VEHICLE IMPACTS ON PETROLEUM CONSUMPTION -----	7-1
A.	GENERAL FINDINGS -----	7-1
B.	SCENARIOS -----	7-2
	BIBLIOGRAPHY -----	8-1

#### Figures

1-1.	The Three Principal Hybrid Vehicle Concepts Explored -----	1-5
2-1.	Study Elements and Process -----	2-3
3-1.	Distribution of HV Configurations vs Fuel -----	3-3
3-2.	Distribution of HV Configurations vs Operating Modes -----	3-4
3-3.	Typical Hybrid Vehicle Power Train Schemes -----	3-6
4-1.	Mission II Travel Patterns -----	4-6
5-1.	Parallel Hybrid Configuration 1 -----	5-7
5-2.	Conventional Power Train -----	5-8
5-3.	Power vs Time for Segment of FTP-Urban Cycle, Mission 2, Vehicle D, MFG = 10%, Lead-Acid -----	5-9

## Figures (contd)

6-1. Cost Analysis Flow Diagram -----	6-2
6-2. Mission 2 Acquisition Cost Ratio -----	6-7
6-3. Mission 2 Operating Cost Ratio -----	6-8
6-4. Mission 2 Life Cycle Cost -----	6-9
6-5. Mission 2-1 Break-Even Gasoline Price -----	6-10
6-6. Mission 2-1 Comparative BEGP Cost Breakdown -----	6-11
6-7. Lead-Acid Battery Purchase Price Requirements for Equivalent Vehicle Life Cycle Cost -----	6-12
7-1. Passenger Car and Light Truck Fleet Size Scenarios -----	7-3
7-2. Fleet Average AVKT Scenarios -----	7-4
7-3. Gasoline Price Scenarios -----	7-4
7-4. Fleet Fuel Economy Scenarios -----	7-6
7-5. Annual Petroleum Consumption Scenarios -----	7-6
7-6. New Car Fleet Fuel Economy with Hybrid Vehicle Market Penetration -----	7-8
7-7. Hybrid Vehicle Market Penetration -----	7-8
7-8. Annual Petroleum Savings with Hybrid Vehicles -----	7-9
7-9. Cumulative Petroleum Savings with Hybrid Vehicles ----	7-9

## Tables

3-1. Hybrid Vehicle Status -----	3-2
4-1. Mission Requirements and Parameters -----	4-1
4-2. Mission Summary -----	4-4
6-1. Battery Cost and Energy Assumptions -----	6-6
7-1. Battery Cycle Life Scenarios -----	7-5

## SECTION I

### EXECUTIVE SUMMARY

#### A. INTRODUCTION

The purpose of this study was to assess the potential of hybrid vehicles as a replacement of the conventional gasoline or diesel fueled internal combustion engine (ICE) vehicle within the next 20 to 30 yr. In particular, the primary purpose of this study was to determine if there are hybrid vehicle designs and applications which are technically and economically viable and offer reductions in petroleum usage large enough to warrant major expenditures of R&D funds. A secondary purpose was to identify critical technical areas where R&D can be most usefully concentrated.

A hybrid vehicle has more than one source of motive power, most commonly an internal combustion engine and an electric motor. Ten years ago, when vehicle emissions were of pressing national concern, hybrid vehicles were investigated as a way of reducing atmospheric pollutants. Now, because of the shift in emphasis to energy conservation and petroleum displacement in particular, a new look at hybrid vehicles was warranted.

The hybrid vehicle concepts assessed in this study use both petroleum fuel and battery-stored electric energy. They all have a primary electric range where only a minimal amount of petroleum fuel is used. This range varies from about 25 km to 100 km depending on the particular design and use pattern. Beyond this range, the vehicles rely on petroleum fuel almost exclusively and operate very much like conventional ICE vehicles.

An electric vehicle can potentially displace 100% of petroleum fuel with electric energy, but is technologically limited, at present, by inadequate performance and range for most applications. The hybrid vehicle is not subject to these limitations, but uses some petroleum fuel to avoid them. However, the amount of petroleum fuel required can be as little as 20% of that required by an equivalent ICE vehicle.

#### B. CONCLUSIONS

The major conclusions reached in the study are:

- (1) Hybrid vehicles have a maximum potential to replace over 80% of the petroleum used by cars and light trucks with electricity by the year 2010.
- (2) The minimum estimated cost of a conversion to such hybrid vehicles would be roughly equivalent to paying \$3.00/gal

for gasoline in 1978 dollars. Considerable improvement in battery and controller costs and vehicle mass production are required to achieve this cost figure.

- (3) Hybrid vehicle costs and the petroleum displacement they provide are directly proportional. The more fuel they displace, the more it costs to displace it. Hybrid vehicles could conceivably replace 40% of the petroleum used by cars and light trucks with electricity by the year 2010 at a cost roughly equivalent to paying \$2.00/gal for gasoline. These vehicles would have smaller battery packs and about half the electric range of the vehicles that would provide 80% as in (1) above.
- (4) No loss of mobility need be suffered by the American public in this conversion. Hybrid vehicles can offer the same payload capacities, performance, range, style, comfort, and amenities as today's cars and trucks--if properly designed and executed.
- (5) The ultimate potential of hybrid vehicles as a viable substitute for the conventional ICE vehicle will be limited not by technology but by high initial and life cycle cost. Present hardware is adequate in terms of physical parameters, but considerable cost reductions are required.
- (6) The critical technical areas where R&D money can be most usefully spent are:
  - (a) System design and development. It remains to be shown that the designs in this study or similar designs can be built in mass producible and driveable forms.
  - (b) Development of low cost, long lived batteries--even at the expense of specific power and specific energy.
  - (c) Development of low cost controllers.

#### C. STUDY SETTING

This study is only a small part of the overall DOE electric and hybrid vehicle program which, in turn, is only a small part of the national effort to solve our energy problems. The study was designed to investigate thoroughly only a piece of the puzzle and leaves to other studies--past, present, and future--the delineation of the remaining pieces and their final assembly. Thus, the study does not compare the potential of hybrid vehicles to electric vehicles, nor the relative costs of synfuel from coal or biomass to HVs, nor the merits

of hydrogen powered vehicles, nor whether mass transit might be the smarter way for the nation to go rather than continued development of personally owned and operated transportation systems. These questions must be addressed by the nation's policy makers as they allocate funds to various avenues of R&D. The results of this study are intended to be only one set of inputs into that process. From this point of view, the study is very narrow in scope in that it is limited to a comparison of hybrid vehicles and conventional vehicles projected into a future that is not too different from 1978.

Another important question that was not addressed directly in this study was that of transportation utility. The hybrid vehicle offers the considerable advantage of fuel flexibility over both the conventional vehicle and the electric vehicle. This allows the owner of a hybrid vehicle to decide in real time which fuel to use based on price and availability. This would be a very attractive feature in a gas rationing situation or in the face of widely fluctuating fuel and electricity prices.

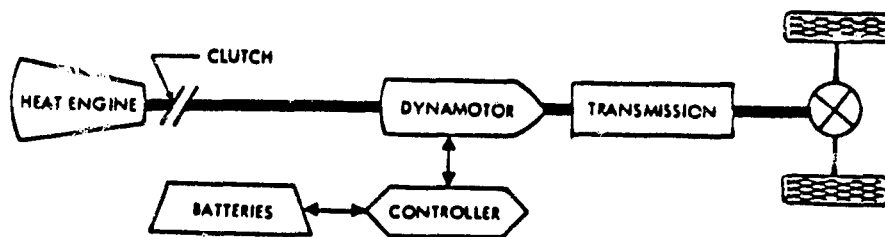
#### D. WORKING QUESTIONS

To evaluate the technological and economic feasibility of hybrid vehicles and their potential impact on national petroleum consumption within the next 20 to 30 yr, a limited number of working questions were formulated. These questions listed below together with answers derived in this study, summarize the conclusions of this study. The rationale for these answers are found in the following chapters and in the detailed analyses behind them that are presented in JPL Document 5030-345, Volumes II through X.

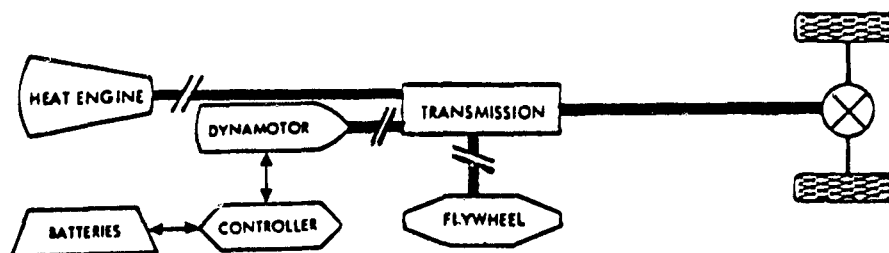
- (1) What are the potential impacts of hybrid vehicles on the national petroleum consumption, under a variety of scenarios?
  - (a) Hybrid vehicles have a maximum potential to displace up to 80% of the petroleum fuel used by comparable ICE vehicles. However, this would require that all vehicles that could be replaced by a hybrid were replaced by a 100 km electric range hybrid. The cost to the nation of achieving this level of petroleum displacement would be roughly equivalent to paying \$3.00/gal for gasoline.
  - (b) It is very unlikely that the maximum potential will ever be achieved. Vehicles will not all be hybrids and all hybrids will not have 100 km electric range unless these conditions are mandated or induced by federal legislation or regulation.

- (c) If the potential of HVs is limited by cost constraints, that is, if we assume that HVs must have equal or lower life cycle cost than ICEs before they can replace them, then the potential of HVs ranges from zero to 40% petroleum displacement depending upon assumptions about battery technology improvements, gasoline price rises, and electricity costs.
- (2) What are the general travel patterns and applications (i.e. missions) of cars and light trucks in the U.S.? For how many such applications are hybrid vehicles appropriate? For which are they best suited?
- (a) Five passenger car missions and two delivery van missions were found to adequately represent the wide range of travel patterns and applications performed by today's fleet of cars and light trucks.
  - (b) Vehicle performance requirements are set by the operating environment rather than the particular travel pattern and application, and are therefore quite similar for all highway capable vehicles. Only minor variations were found in the vehicle performance requirements developed for each of the seven missions.
  - (c) Hybrid vehicles were found to be most effective in reducing the consumption of petroleum fuels--and most cost effective--on missions with low speed stop-and-go driving conditions. They were the least effective on missions with a high proportion of highway driving.
  - (d) Hybrid vehicles were found to be capable of reducing petro-fuel consumption considerably on all seven missions studied.
- (3) What are the "best" hybrid vehicle designs assuming near-term or advanced technology? "Best" meaning the most petroleum fuel efficient yet life cycle cost competitive as compared to ICE vehicles with equivalent design requirements and transportation functions. (The power train schemes of the three principal hybrid vehicle concepts explored in this study are shown in Figure 1-1).
- (a) In the long-term, the parallel hybrid with a flywheel secondary storage unit was found to be the most attractive hybrid design of the concepts considered.

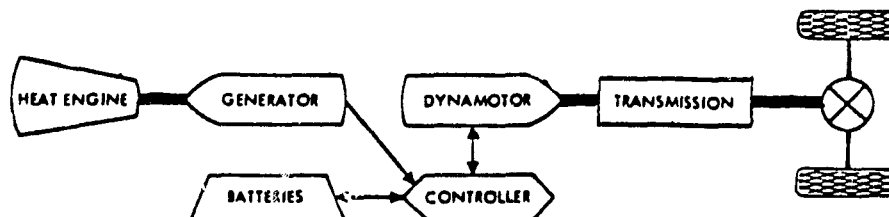
- (b) In the near-term, however, the basic parallel hybrid vehicle design was found to be the most attractive, since it does not require development of a flywheel-transmission subsystem and associated controls.
- (c) The series hybrid was the least attractive of the three principal hybrid vehicle concepts explored in this study. They are intrinsically heavier, less fuel efficient, and more expensive than parallel hybrids when designed using the same component technologies.



a. Parallel Hybrid



b. Flywheel Hybrid



c. Series Hybrid

Figure 1-1. The Three Principal Hybrid Vehicle Concepts Explored

- (4) What are the major cost elements of the various hybrid vehicle designs? Under what conditions would hybrid vehicles become life cycle cost competitive?
- (a) The purchase price is intrinsically higher for a hybrid vehicle than for a comparable ICE vehicle by a factor of about 1.2 to 2.0.
  - (b) The cost trade-off of batteries and electricity versus gasoline or diesel fuel is by far the most important cost consideration.
  - (c) The most attractive of the hybrid vehicle designs, based on present and near-term technology, are life cycle cost competitive with comparable ICE vehicles at gasoline prices on the order of \$2.00 to \$2.50/gal (in 1978 dollars). These vehicles generally displace about 50% of the direct petroleum consumed by comparable ICE vehicles.
  - (d) For the majority of vehicle missions, more petroleum displacement requires greater electric range and larger battery packs and consequently results in higher purchase price and life cycle cost.
- (5) What are the impacts of near-term and advanced battery technology on the life cycle cost of hybrid vehicles?
- (a) Lower battery cost and longer cycle-life are more important to hybrid vehicles than higher specific energy and specific power.
  - (b) If the DOE R&D cost goals for batteries are just met, the advanced lead-acid battery would be slightly more cost competitive than nickel-zinc or sodium-sulphur batteries.
- (6) How well has the hybrid vehicle concept worked out when implemented in actual on-road vehicles?
- (a) All of the hybrid vehicles built to date were essentially proof-of-concept vehicles. Only a very few of the 81 vehicles reviewed in this study were ever intended to be commercially produced, and none of them can be considered a mature design in engineering or manufacturing terms. On this basis, it is not appropriate to make any conclusions about the commercial and economic viability of hybrid vehicles or their petroleum displacement potential from the vehicles that have been built to date. Many of the vehicles were operated successfully and could be said to have "proved their concept."



## E. STUDY ASSUMPTIONS

A large number of assumptions and estimates were required in the course of this study, most of which are described in the appropriate sections of this report and JPL Document 5030-345, Volumes II through X. A few crucial assumptions were made or given to the study team as part of the study charter which shaped the emphasis, scope, and approach of the study. These are discussed below.

- (1) Given: It is desirable to replace petroleum with electricity as a transportation fuel.
- (2) Assumed: It is desirable to maintain or improve the present level of mobility in the United States. Accordingly, several subsidiary assumptions were made:
  - (a) Travel and vehicle purchase trends would continue essentially as they have been for the last ten years.
  - (b) Road construction trends would continue as in the past and road system designs would not change dramatically from current practice.
  - (c) The nationwide speed limit would be at or above the current 55 mi/h limit.
- (3) Definition: "Potential" (1) something that can develop or become actual but will not necessarily happen, (2) credibly possible. The measurement of "potential" is subjective. What is credibly possible to one observer is absurdly ridiculous to another and the obvious wave of the future to a third. In this study, a hybrid vehicle is assumed to possess the potential to replace an ICE vehicle in some future marketplace if it meets the following criteria:
  - (a) The HV can perform the required transportation mission at least as well as the conventional vehicle.
  - (b) The HV can operate successfully in the same traffic environment as the conventional vehicle without increased risk of accident involvement and no adverse impact on that traffic system.
  - (c) The HV can offer a similar vehicle "package" in terms of general styling, passenger seating arrangements, and so forth.
  - (d) The HV can offer the same comfort, amenities, and options normally available with conventional vehicles.

- (e) The HV offers at least a 20% reduction in direct petro-fuel consumption. Simple load-leveling of the heat engine with no "electric range" provides about a 20% reduction.
  - (f) The HV is cost "competitive"; preferably, at least life cycle cost equivalent.
- (4) All of the HV designs studied were assumed to be capable of being built into an integrated vehicle and mass produced.
- (5) A number of important issues were not addressed in this study because they are the subjects of other studies being performed as part of the DOE EHV Program or other government programs. These include the following:
- (a) No assessment of institutional, environmental, or economic impacts was attempted.
  - (b) No assessment of the capability of the auto industry to produce large numbers of hybrid vehicles was attempted.
  - (c) No assessment of the capability of the utility industry to supply the required electrical energy was attempted.
  - (d) No assessment of the availability of source fuels to generate the required electrical energy was attempted.

## SECTION II

### APPROACH

The study employed a basic systems analysis approach with the following steps:

- (1) Define the objective function. In this case, the objective was to maximize national petroleum displacement at minimum cost.
- (2) Define the functional requirements or sets of functional requirements. In this case, the functional requirements are the trip purposes, payloads, and travel patterns the vehicles must perform, i.e., the vehicle "missions".
- (3) Define the system requirements. Payload capacity and performance requirements were the principal system-level requirements defined for this study.
- (4) Review the state of the art and develop alternative design solutions and corresponding subsystem requirements. A large number of alternatives were looked at in varying levels of detail.
- (5) Select the most promising alternatives and simulate their operation over the missions.
- (6) Estimate the purchase, operating, and life cycle costs of those alternatives.
- (7) Based on the results of steps (4), (5), and (6) select the "best" HV design for each mission at any point in time in the future (under a variety of economic and technology development scenarios). Estimate the potential impact on national petroleum consumption if these vehicles replaced their conventional counterparts.

The analysis was performed in five subtasks which will be described briefly in this summary and are described in greater detail in Volume II. They correspond roughly but not exactly to the steps described above and were: (1) hybrid vehicle review, (2) mission analysis, (3) power train analysis, (4) cost analysis, and (5) petroleum impact analysis.

#### A. OBJECTIVES AND SCOPE

The objective of this study was to assess the potential of hybrid vehicles as a replacement for the conventional ICE vehicle within the

next 20 to 30 yr. More particularly, the primary objective of the study was to determine if there are hybrid vehicle designs and applications which are technically and economically viable and offer potential reduction in petroleum usage large enough to warrant major expenditures of R&D funds. A second objective was to identify critical technical areas where R&D can be most usefully concentrated.

The scope of this study was limited to the analysis of passenger cars and light duty trucks for highway use. It was furthermore limited to "dual-fuel" hybrid vehicles which utilize wall plug electricity along with one petroleum based liquid fuel (e.g., gasoline or diesel).

## B. APPROACH

Previous studies of hybrid vehicles have reported generally discouraging results. Expected petroleum savings, if any, were moderate, but the economics were negative. Only a few of the studies considered explicitly the question of displacing petroleum with wall plug electricity. The more comprehensive studies were forced to be too general in their consideration of vehicle designs and mission definitions to be able to analyze the full potential of their hybrid vehicle concepts. The more specific studies show more encouraging results but often suffer from inappropriate selection or definition of the mission for the explored hybrid vehicle concept.

In an attempt to overcome these shortcomings of previous studies, a primary concern of this study has been to balance the levels of detailed analysis by emphasizing all of the four key elements of the study (i.e., the mission, power train, cost, and petroleum impacts analysis). The fifth study element, the hybrid vehicle review, was carried out independently and at a lower level of effort.

The overall process of this study is summarized in Figure 2-1 with the following explanatory notes:

- (1) Hybrid Vehicle Review. Identify and review hybrid vehicles built within the last ten years or designed to be built in the near future.
  - (a) Worldwide, 81 hybrid vehicles were reviewed.
  - (b) These vehicles were characterized and categorized.
- (2) Mission Analysis. Develop a limited set of potential hybrid vehicle missions which are representative of the use patterns of significant portions of the light duty vehicle fleet in the United States.

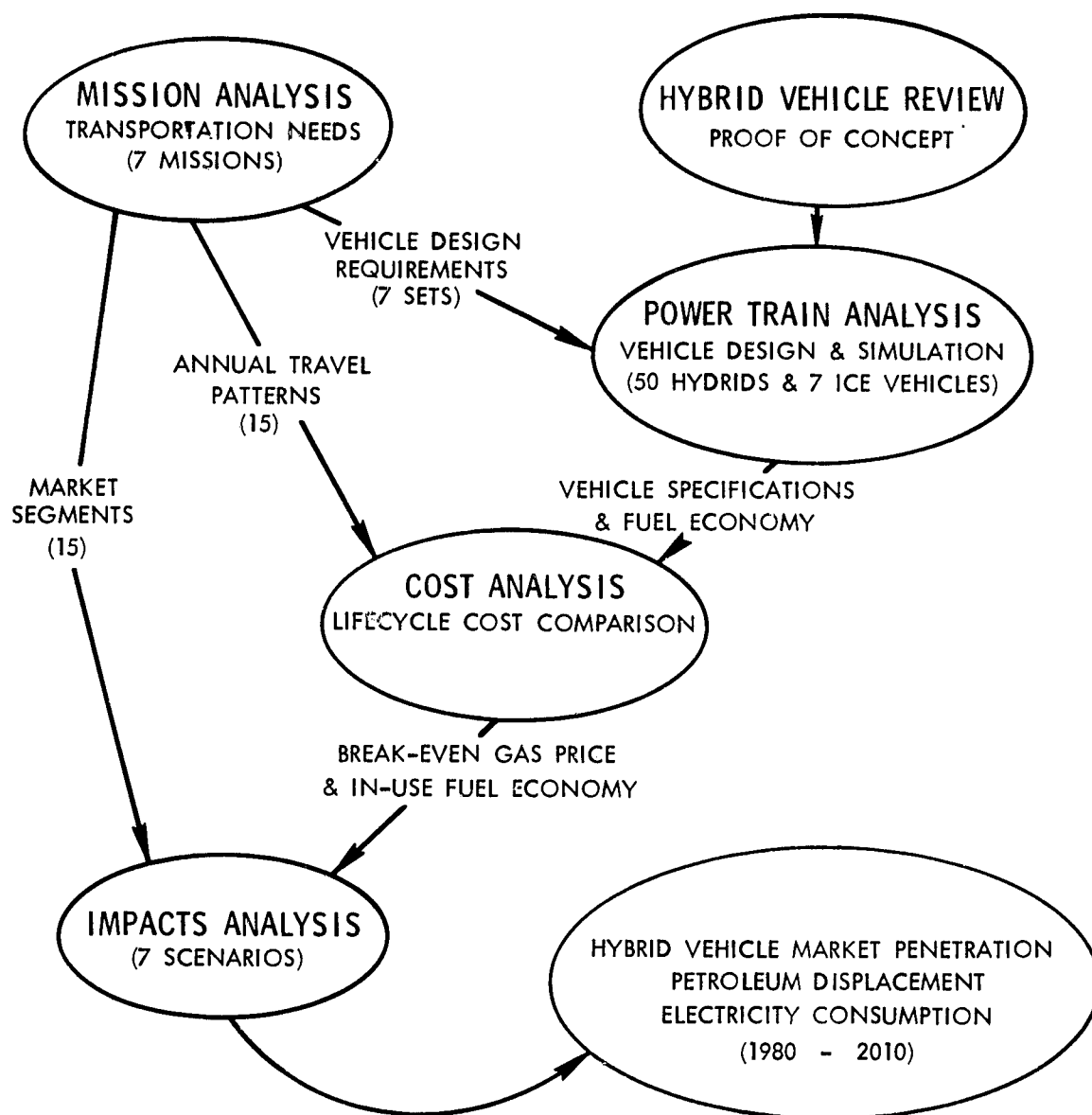


Figure 2-1. Study Elements and Process

- (a) Seven missions were developed of which five could be considered significant.
  - (b) A set of vehicle design requirements was specified for each mission.
  - (c) Each of the five significant missions was again stratified in terms of two or three typical annual travel patterns, representative of specific market segments. Hence, a total of fifteen market segments/annual travel patterns were developed within the mission spectrum.
- (3) Power Train Analysis. Select the most promising hybrid power train concepts and representative advanced battery types for further analysis. Design and simulate, for each set of vehicle design requirements (missions), a limited number of hybrid vehicles and a conventional ICE vehicle for baseline comparison (i.e. a set of equivalent mission performance vehicles, for each mission).
- (a) Three promising hybrid power train concepts were developed: a parallel, a parallel-flywheel, and a series hybrid.
  - (b) Three promising advanced battery types were selected: the "advanced" lead-acid, the nickel-zinc, and the sodium-sulphur battery.
  - (c) Each vehicle type was designed to provide two or three different "primary electric" ranges for each mission.
  - (d) Detailed vehicle specifications were developed for each of the vehicles.
  - (e) Performance and fuel consumption characteristics were simulated for each vehicle using digital computer simulation programs developed for this purposes.
- (4) Cost Analysis. Simulate annual fuel consumption (in-use fuel economy) for each vehicle, and estimate its purchase and life cycle cost. Make life cycle cost comparisons between the hybrids and the ICE vehicle within each mission and calculate the gasoline price required to reach equivalent life cycle cost (i.e., the break-even gasoline price, BEGP).
- (a) A set of BEGP's were calculated parametrically for each hybrid vehicle, depending on (1) the specific

annual travel pattern, (2) the battery cycle life, and (3) the level of purchase price subsidy.

- (b) Annual fuel consumption (electricity and gasoline) was calculated for each hybrid and ICE vehicle.
- (5) Petroleum Impacts Analysis. Assess the potential impacts of the simulated vehicles on petroleum and electricity consumption, under a limited set of consistent scenarios.
  - (a) A total of six scenarios were generated to test the effects of battery cycle life, subsidy, and gasoline price forecast, on the study results.
  - (b) Hybrid vehicle market penetration and the resulting fleet fuel economies and annual fuel consumption rates were projected for each scenario.

#### C. CONCEPTS

There are four principal concepts which are essential to the overall study process:

- (1) Equivalent mission performance vehicles (EMP vehicles).
- (2) Hybrid vehicle break-even gasoline price (BEGP).
- (3) Vehicle replacement.
- (4) Petroleum displacement.

##### 1. Equivalent Mission Performance Vehicles

A set of equivalent mission performance (EMP) vehicles is a set of vehicles that are designed to perform the same mission at the minimum required performance level. Each vehicle has the same payload capacity. Each vehicle just meets one or more of the performance requirements and exceeds the rest. They may differ in their maximum performance capabilities.

For each mission, one EMP vehicle is an ICE vehicle which is designed to meet the mission requirements and optimized for minimum fuel consumption. This vehicle is used as the baseline upon which HV fuel savings and relative costs are based. Thus, the study does not compare an HV with inferior performance to a conventional performance ICE vehicle.

Seven different sets of EMP-vehicles, one set for each mission, have been developed in this study. The viability of hybrid vehicles

is based exclusively on comparisons within each set of EMP-vehicles; i.e., between vehicles designed for and serving identical transportation functions.

## 2. Hybrid Vehicle Break-Even Gasoline Price

The break-even gasoline price (BEGP) of a hybrid vehicle is defined as the price of gasoline for which the present value of life cycle costs of a hybrid vehicle and its comparable ICE vehicle (within the same set of EMP-vehicles) are identical, when simulated over the same annual travel pattern.

This parameter is used as the basic measure of cost effectiveness because it contains all of the elements of life cycle cost of both the HV and its ICE comparator. However, this should not be taken to mean that the HV will be cost effective if gas prices rise to that level. This is not the case. The costs of all other goods and services contributing to the total life cycle cost would also rise at varying rates with the cost of gasoline and change the overall relationships.

## 3. Vehicle Replacement

For a given scenario (i.e., a specific level of subsidy, battery cycle life and gasoline price), a hybrid vehicle is considered a potential replacement for an ICE vehicle if its BEGP is equal to or lower than the projected gasoline price. In each of these scenarios the price of gasoline is allowed to rise relative to all other prices in real dollars.

When a hybrid vehicle becomes a replacement vehicle in this sense and the projected gasoline price increases over time, it is assumed to dominate its particular market segment of the new vehicle fleet. If there is more than one replacement hybrid vehicle within the same market segment at a particular point in time, the one with the highest petroleum fuel displacement potential is assumed to penetrate the market segment.

## 4. Petroleum Displacement

The terms "petroleum displacement," "petroleum savings," and "reduced petroleum consumption" have been used as identical concepts in this study. Petroleum displacement is defined as the difference between the direct gasoline or diesel consumption of hybrid vehicles and their comparable ICE competitors and is based on the assumption that the additional electricity consumed by the hybrids will be generated through the use of nonpetroleum fuels.



### SECTION III

#### HYBRID VEHICLE REVIEW

A review of hybrid vehicles built during the past ten years or planned to be built in the near future was conducted in support of this study. The primary purpose for this review was to generate an updated and more extensive data base on the state-of-the-art of hybrid vehicles than reported in previous studies.

Furthermore, an attempt has been made to classify and analyze these vehicles to get an overall picture of their key characteristics. For the purposes of this review, hybrid vehicles were defined as any vehicle with more than one energy storage system (e.g. liquid fuels, batteries, flywheels, etc.). The DOE definition and the definition used in all other elements of this study, however, is a vehicle which uses more than one fuel--one of which is wall plug electricity.

The review included on-road hybrid passenger cars, trucks, vans and buses. In support of the initial phase of the data collection activities, visits were made to seven different sites in the U.S., covering eight hybrid passenger cars, one hybrid van, and one hybrid bus.

#### A. GENERAL FINDINGS

All of the vehicles identified in this vehicle review are experimental and basically proof-of-concept vehicles. While a few of these vehicles are meant to be preproduction prototypes, none of them has actually led to any production greater than two-of-a-kind.

A total of 81 hybrid vehicles were identified worldwide. Twelve of them are still at the design stage or planned to be built in the near future, while the rest have been built within the last ten years.

Most of these vehicles have been operated, and at times modified, without changing the original arrangement of their major power train components. Only three vehicles (all passenger cars) have at one time or another been modified so dramatically that they each can be said to represent more than one hybrid configuration. Thus, the 81 vehicles identified were found to represent a total of 85 hybrid vehicle configurations. It should be noted that existing hybrid vehicle designs which are not presently intended to be implemented in an actual vehicle have been excluded.

A more detailed count of the reviewed hybrid vehicles in terms of their present status, national origin, and type of vehicle is given in Table 3-1.

Table 3-1. Hybrid Vehicle Status

Present Status	Passenger Cars		Trucks and Vans		Buses		Total
	USA	Foreign	USA	Foreign	USA	Foreign	
Running Condition	19	6	2	6	2	2	37
Out of Order	1	0	0	0	0	0	1
Disassembled	2	0	1	0	1	0	4
Status Unknown	14	8	3	1	0	1	27
Subtotal Built to date	36	14	6	7	3	3	69
Planned for the near future	9	1	2	0	0	0	12
Total	60		15		6		81

Most of the 85 reviewed hybrid vehicle configurations are conversions of conventional production vehicles. Of the 64 configurations where chassis and body style are known, there are 45 (or 70%) such conversions and 6 (or 10%) with a modified production chassis and/or custom made fiberglass body. Only 13 (or 20%) are specially built from the ground up.

#### 1. Fuel

Almost 70% (59 configurations) of the reviewed configurations have been identified as "multiple fuel electric hybrids" (the present DOE definition of a hybrid vehicle) while only 18% (15 configurations) have been identified as single fuel hybrids (Figure 3-1).

#### 2. Storage

All of the 74 configurations with known type(s) of fuel and storage are "multiple storage hybrids". It should be noted that the "multiple storage" term was initially used to identify the hybrid vehicles in this review.

#### 3. Operating Modes

All of the 59 hybrid vehicle configurations with known operating mode(s) are designed to be operated in one or more of the following four operating modes exclusively (see Figure 3-2):

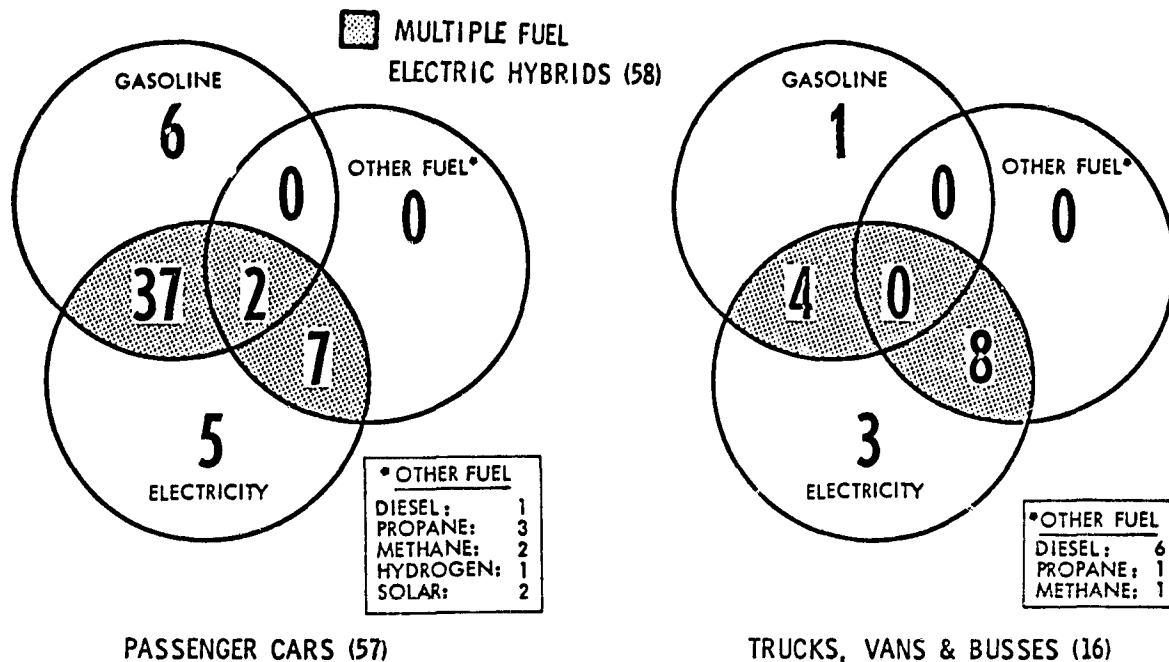


Figure 3-1. Distribution of HV Configurations vs Fuel

- (1) Heat Engine On-Off. The heat engine will automatically be turned on or off depending on the need for power and/or energy or at certain vehicle speeds.
- (2) Heat Engine Continuous. The heat engine will run continuously either at a constant speed or a variable speed depending on the need for power and/or energy.
- (3) All/Primary Heat Engine. The heat engine will deliver most or all of the needed power and energy to drive the vehicle, and in some cases even to recharge batteries (or other energy storage devices). In cases of extreme power demands, the batteries (or other energy storage devices) might be utilized as a supplementary power source.
- (4) All/Primary Electric. The batteries will deliver most or all of the needed power and energy to drive the vehicles. In cases of extreme power demands, the heat engine might be utilized as a supplementary power source.

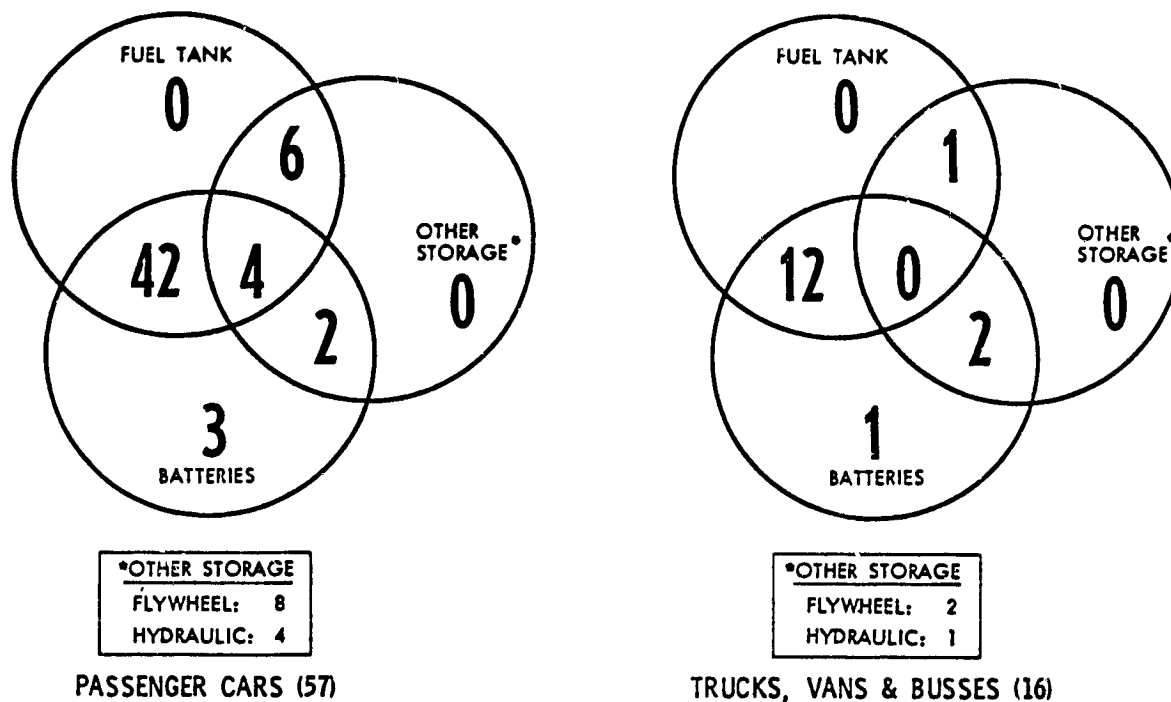


Figure 3-2. Distribution of HV Configurations vs Operating Modes

#### 4. Power Plants

About 75% of the 59 "multiple fuel electric hybrids" (identified above) are using a conventional Otto cycle engine combined with some kind of a d.c. motor.

Most often the parallel hybrids (i.e., hybrids with direct drive from the heat engine to the driveshaft) were found to have no separate generator as opposed to the series hybrid. Four parallel configurations, or about 20% of the parallel hybrids, differ from this general trend.

#### 5. Hybrid Vehicle Performance

Very little reliable performance data is available on HV's, and no conclusions were drawn from the bits and pieces of information acquired.

## 6. Power Train Schemes

Hybrid vehicle configurations were classified in terms of their particular power train scheme. A total of 20 power train schemes, distributed on five major configuration classes, were required to cover all of the 61 hybrids with a known power train scheme. The distribution among the five basic classes is listed below, and the most typical variation within each class is shown in Figure 3-3.

Class S:	Series Hybrids	(3 Variations/28 HVs)
Class P:	Parallel Hybrids	(6 Variations/16 HVs)
Class F:	Flywheel Hybrids	(6 Variations/9 HVs)
Class D:	Dual-Battery Hybrids	(1 Variation/4 HVs)
Class O:	Other Hybrids	(4 Variations/4 HVs)

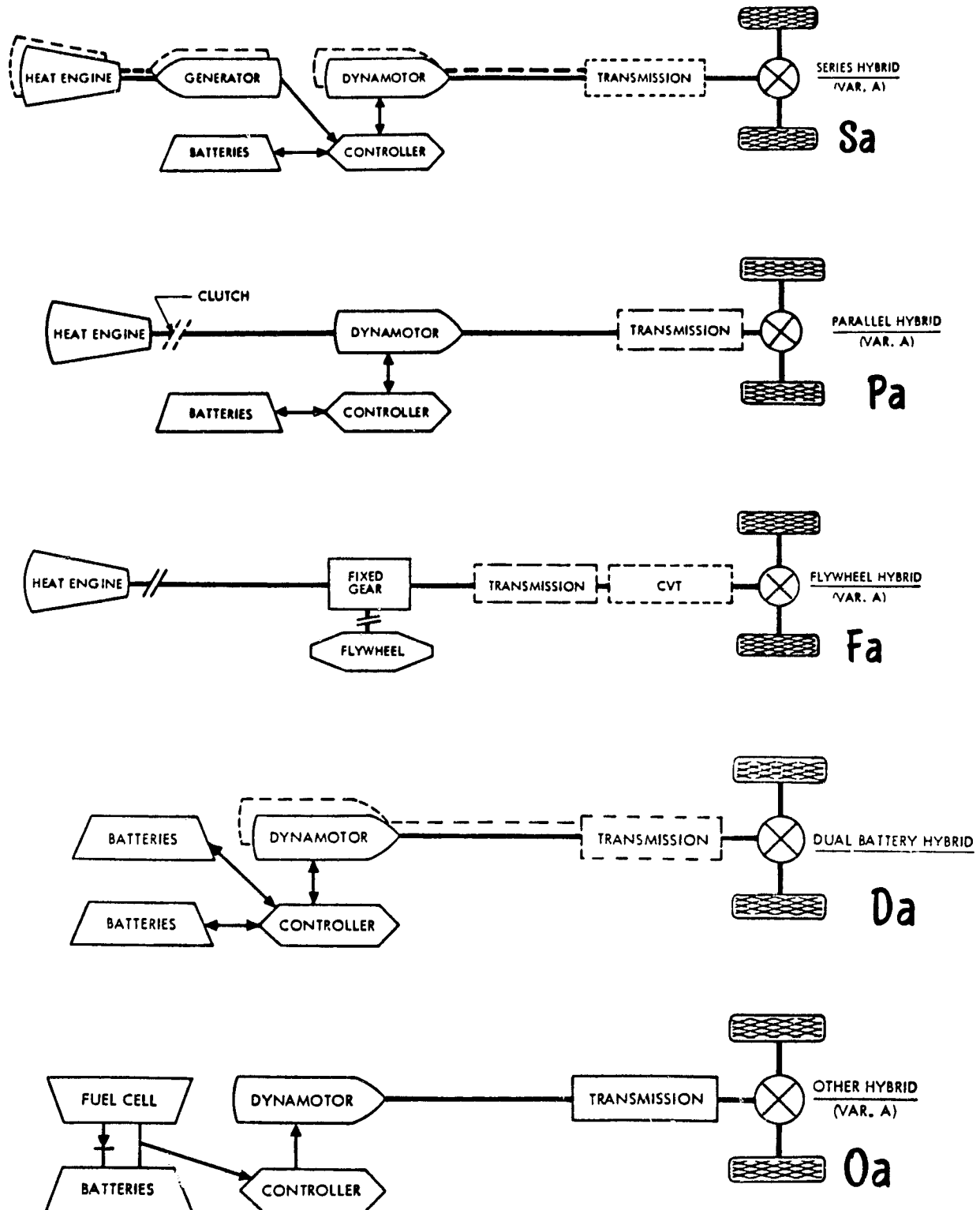


Figure 3-3. Typical Hybrid Vehicle Power Train Schemes

## SECTION IV

### MISSION ANALYSIS

This section summarizes the seven vehicle missions used in this study. The details of how these missions were selected and constructed can be found in JPL Document 5030-345, Vol. II.

For the purposes of this study, each mission is described with respect to its transportation functional requirements as well as vehicle design requirements, in terms of the requirements and parameters shown in Table 4-1.

The formulation of such detailed descriptions, which merges a specific set of transportation functions with a specific set of vehicle design requirements within each mission, was motivated by the concept of the equivalent mission performance vehicle (EMP-vehicle). The EMP-vehicle concept is founded on the notion that the comparison of alternate vehicle propulsion systems or other vehicle subsystems makes sense only if it is done at the vehicle systems level as opposed to the subsystems level itself, and then only if such comparisons are

Table 4-1. Mission Requirements and Parameters

Requirements	Parameters
1) Transportation purposes	Trip purposes Market share
2) Driving conditions	Driving cycles
3) Travel pattern	Annual frequency distribution of km/day
4) Payloads	Average payload Passenger and payload capacity
5) Minimum vehicle performance	Top and cruise speed Acceleration Gradeability
6) Basic vehicle characteristics	Coefficient of drag Rolling resistance Frontal area Basic body and chassis weight

limited to vehicles with equivalent transportation functions, overall performance capabilities, and nonpropulsion technology.

The marketability of hybrid vehicles in relation to their specific mission was not addressed as a separate issue. They were assumed to be potentially marketable if they could adequately perform the mission for which they were designed, and if they were life cycle cost competitive with their EMP-vehicle counterparts. Under such conditions it was assumed that some vehicle manufacturers could package, style, advertise, and sell them so that they would successfully penetrate the market segment represented by their particular mission in a normal new-product manner.

#### A. GENERAL FINDINGS

Considerable effort was expended in this study to produce a set of well-defined, realistic missions with a wide variety of travel patterns, driving conditions, and transportation functions. A wide variety of vehicle specifications and performance requirements were expected to come out of the analysis. However, the answers to the following working questions did not confirm these expectations.

- (1) Do mission specifications vary widely with transportation functions?

No. The vast majority of current vehicle missions are amazingly similar. Travel patterns in terms of daily driving distributions tend to have very similar shapes even if the average annual vehicle kilometers traveled (AVKT's) vary dramatically.

- 2) Do performance requirements vary widely with the missions?

No. Performance requirements are set by the operating environment rather than the individual vehicle mission functions or travel patterns and therefore are quite similar for all vehicles which operate on today's streets and highways.

#### B. MISSION SELECTION

One of the basic assumptions in developing the automobile missions was that the travel patterns exhibited by the 1969 Nationwide Personal Transportation Study (NPTS) will continue in the near future. The sudden rise in gasoline prices contributed to a temporary drop in average annual vehicle kilometers traveled (AVKT) in 1973-74. However, since 1974, AVKT's have resumed their rise, supporting this assumption. The details of the travel patterns could have changed



considerably in the last ten years, however. A new survey was taken in 1977 and that data should be reviewed when it becomes available sometime in 1979 to determine if any updating of this mission analysis is required.

Another basic assumption behind the analysis is that petroleum resources will become scarce in the future. This scarcity will be passed to the consumer in the form of either higher gasoline prices or restricted supplies, and it is assumed that consumers will react by placing greater emphasis on fuel costs and fuel consumption in their purchase decisions.

The basic assumption in selecting hybrid vehicle missions is that the mobility of motorists in the post-1985 era will remain the same as it is today. Based on the criteria established for mission selection, spectrum coverage of mission space, and the future petro-fuel scenario, vehicle missions shown in Table 4-2 were selected.

The seven missions were selected so that the total mission set would meet the following criteria:

- (1) The mission set should account for a significant proportion of transportation fuel consumption, current or projected.
- (2) A wide variety of vehicle types should be included, representing both current vehicles and some hypothetical vehicles.
- (3) A wide variety of travel patterns should be represented.
- (4) A wide variety of driving conditions should be represented.

All of these criteria were met to a large degree.

A set of transportation requirements were developed for each mission which included the trip purposes that must be served, payloads that must be carried, distances that must be traveled and their distribution on a daily and annual basis, and typical driving conditions.

#### C. TRANSPORTATION REQUIREMENTS

##### 1. Trip Purposes and Payloads

The trip purposes and corresponding passenger and payload capacities were derived from the NPTS data on a coordinated basis to best match the general mission functions.

Table 4-2. Mission Summary

MISSION No.	I		II		III		IV		V		VI		VII	
MISSION TYPE	COMMUTER		FAMILY RUNABOUT		FAMILY ALL PURPOSE		LIMO/TAXI		VACATION RENTAL		VARIABLE ROUTE VAN		FIXED ROUTE VAN	
PASSENGER CAPACITY	2		4		6		6		6		2		2	
TOTAL PAYLOAD CAPACITY (kg)	190		375		600		600		600		890		640	
AVERAGE PAYLOAD (kg)	90		120		150		200		300		750		500	
EPA TEST PAYLOAD (kg)	150		150		150		150		150		150		150	
BASELINE CARRIAGE WEIGHT (kg)	500		900		1100		1100		1100		1400		1400	
FRONTAL AREA (m <sup>2</sup> )	1.7		1.8		1.9		1.9		1.9		2.7		2.7	
DRAG COEFFICIENT	0.40		0.40		0.38		0.38		0.38		0.60		0.60	
ROLLING RESISTANCE COEFFICIENT	0.010		0.010		0.010		0.010		0.010		0.010		0.010	
SUSTAINED SPEED (km/h)	100		100		100		100		100		100		100	
ACCELERATIONS (secs):														
0-50 km/h	6		6		6		6		6		7		7	
30-55 km/h	4		4		4		4		4		5		5	
60-90 km/h	9		9		9		9		9		10		10	
0-100 km/h	14		14		14		14		14		18		18	
GRADEABILITY:														
5% AT 90 km/h, km	2		2		2		2		2		2		2	
7% AT 50 km/h, km	0.4		0.4		0.4		0.4		0.4		0.4		0.4	
20% AT 20 km/h, km	0.2		0.2		0.2		0.2		0.2		0.2		0.2	
AVKT (km/yr) - MISSION PERCENTILE	12,857	31.5%	9,027	31.5%	10,627	31.5%			48,400	50%	8,700	50%	11,300	50%
DAILY TRAVEL (km/d)	50%-ile	23	10		11		-		128		20		41	
	75%-ile	42	31		34		-		193		33		45	
	90%-ile	78	66		79		-		292		48		52	
AVKT (km/yr) - MISSION PERCENTILE	18,692	58.5%	14,664	58.5%	16,264	58.5%	48,400	50.0%	-		-		-	
DAILY TRAVEL (km/d)	50%-ile	45	25		27		132		-		-		-	
	75%-ile	60	54		59		156		-		-		-	
	90%-ile	98	99		116		226		-		-		-	
AVKT (km/yr) - MISSION PERCENTILE	24,496	77.4%	21,456	77.4%	23,056	77.4%	-		-		16,300	90%	22,060	90%
DAILY TRAVEL (km/d)	50%-ile	70	43		46		-		-		39		80	
	75%-ile	86	80		87		-		-		67		92	
	90%-ile	119	141		159		-		-		107		100	
DRIVING CYCLE	4 URBAN FOLLOWED BY ALL HIGHWAY (60% U, 40% H)		5 URBAN FOLLOWED BY ALL HIGHWAY (60% U, 40% H)		5 URBAN FOLLOWED BY ALL HIGHWAY (60% U, 40% H)		1U, 50N, 1U, 30N, 1H, 30N, 2U, 10N, END (20% U, 10% H, 70% N)		1U, 13H, 2U, 13H, 1U, END (10% U, 90% H)		6 URBAN FOLLOWED BY ALL HIGHWAY (80% U, 20% H)		46V, 1U, 46V 1HV, 46V REPEAT (20% U, 10% H, 70% V)	

U = EPA URBAN CYCLE

H = EPA HIGHWAY CYCLE

N = NEW YORK CITY CYCLE

V = VAN CYCLE

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## 2. Driving Cycles

Driving cycles were constructed for each mission using the Federal Urban and Highway cycles, the New York City emissions cycle and the Aerospace van cycles to represent the typical driving conditions the vehicles would encounter. Some compromises were required to facilitate vehicle simulations and keep the cost of analysis within bounds. The end result was that the effective ratios of urban/highway driving were more heavily weighted toward urban driving (70/30) than the current EPA 55/45 split.

## 3. Travel Patterns

The travel patterns for passenger vehicles were drawn from NPTS data by assuming a Poisson distribution of trip frequency and using a Monte Carlo technique to obtain the daily travel distributions. A typical result is illustrated in Figure 4-1 for 4-passenger family cars. Daily travel patterns for the commercial vehicles were constructed by hand based on the data and assumptions described in Volume II of this report.

## D. VEHICLE DESIGN REQUIREMENTS

The basic criteria for choosing the performance requirements for hybrid vehicles were safety and non-interference with existing traffic patterns. The performance requirements are specified in terms of top speed, acceleration capability, and gradeability. The specific values chosen for the technical aspects discussed in this section can be found in Table 4-1. These requirements are at the low performance range of today's vehicles.

### 1. Sustained Speed

All hybrid vehicle missions described in this report assume freeway capabilities for the vehicle. This results in a requirement for a cruise speed of 88 km/h (55 mi/h) with a 25 km/h headwind, no grade. However, a no-wind specification was easier to work with in the design phase of the study, so this specification was translated into a top speed of 100 km/h with no wind for all vehicles. The specification of a lower top speed might have significant adverse impact on vehicle safety in normal traffic.

### 2. Acceleration

Acceleration requirements are critical in terms of both safety and impact on existing traffic. Several types of acceleration

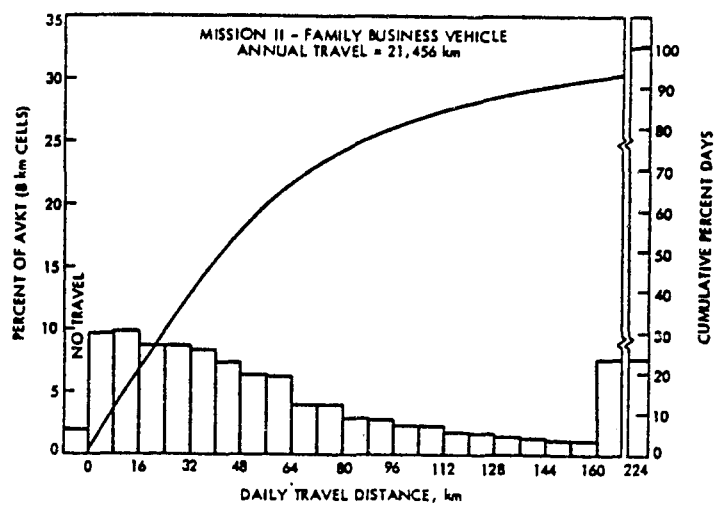
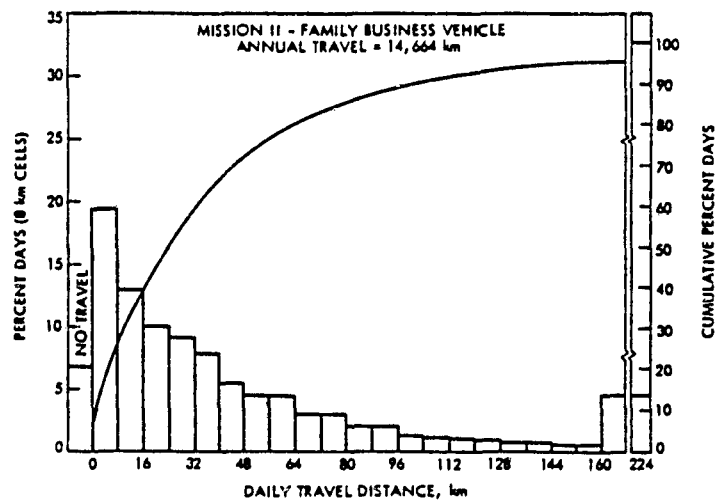
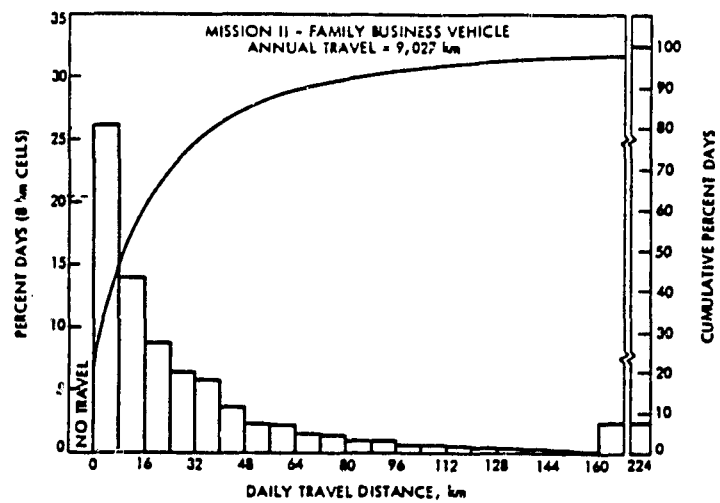


Figure 4-1. Mission II Travel Patterns

requirements have been specified: low speed acceleration, low speed pass, freeway entrance and freeway merge. The most stringent requirement placed on acceleration capability in this study was the requirement to be able to enter onto a freeway and is based on acceleration from a standing start to 64 km/h (40 mi/h) up a 7% grade ramp within 300 m. A level merging lane long enough to allow acceleration to 80 km/h (50 mi/h) is assumed to be available as is the case in the vast majority of ramps. Through the use of several computer simulation programs, it was determined that this was essentially equivalent to an acceleration of 0-100 km/h in 14 s on level grade. The simpler requirement was chosen because of the greater ease of calculation and simulation.

There are other reasons to require good performance even in lower speed regimes. The introduction of large numbers of low acceleration vehicles in the mix of traffic could have a profound impact on the traffic flow. Slower accelerating vehicles tend to increase the acceptance gap. A low performance car merging from a ramp into a 96 km/h stream of given density would wait about six times longer for a gap sufficiently large to avoid turbulence than a car of high performance. Inclusion of low performance vehicles in the traffic stream tends to increase the critical gap, resulting in delays.

According to National Safety Council data, the acceptance of inadequate gaps (right-of-way violation) is a primary cause of right angle collisions which constitute 16.4% of all accidents and 48.5% of those which occur at intersections.

These considerations led to the requirement that hybrid passenger vehicles must have low-speed acceleration capability sufficient to keep up with normal traffic which was determined to be 0-50 km/h in 6 s. Most conventional vehicles can accelerate from 0-50 km/h in less than 4 s, but do not normally use this full capability.

The 0-100 km/h requirement turned out to be the dominating power requirement for all vehicle designs and all missions and, therefore, deserves some further discussion. The passenger car requirement of 0-100 km/h (0-62 mi/h) in 14 s is at the low performance end of the 1979 automobile spectrum according to Road & Track data. Most diesel engined cars are 1 s to 3 s slower. A rough sensitivity analysis was performed by estimating the effect of raising the requirement to 10 s or lowering it to 20 s for both the HV and its conventional comparator. The results indicate that while both the HV and the ICE fuel consumption increases with higher performance and drops with lower performance, the change in break-even gas price and fuel displacement of the the HV is negligible. If anything, the HV is slightly more attractive in the high performance end of the spectrum.

### 3. Gradeability

Estimates of highway grades in U.S. show the following distribution:

Grade	Percent of U.S. Highways
3% and less	63.7 (Urban)
4%-6%	32.0
7%-9%	3.9
Greater than 9%	0.3

The gradeability requirements were specified so as to ensure minimum speed degradations on freeways, ramps, and city streets. They are adequate for driving on most of the U.S. highways and streets.

The requirements for trucks and vans (Missions VI and VII) are reduced somewhat from passenger cars to levels more representative of current commercial vehicles.

### 4. Basic Vehicle Characteristics

Basic vehicle characteristics are specified for each mission so that comparisons can be made between alternate vehicles and alternate hybrid vehicle configurations. Vehicle parameters held constant for vehicles being compared are vehicle weight without propulsion system, frontal area, coefficient of rolling resistance and coefficient of drag. Note that the vehicle weight without propulsion system does not include weight propagation effects which are a function of the propulsion system. It is meant to be the minimum weight required to enclose and carry the required payload and a conventional ICE power train. All of these characteristics are projections into the 1985 time frame and are meant to represent the average for that vehicle class rather than the best achievable value.

## SECTION V

### POWER TRAIN ANALYSIS

The power train analysis portion of this study was by far the most difficult and complex part of the effort. The objectives of this part of the task were to find the "best" hybrid power trains for each vehicle/mission set, simulate their electricity and fuel consumption over the mission, provide this data and a weight breakdown to the cost analyst, and refine and optimize the vehicles based on the cost data. Much of the analysis was carried out in parallel with the mission analysis and prior to the availability of the computer program for calculating vehicle costs. These facts and constraints of time and budget required many compromises between the desire to be comprehensive in the search and the need to perform very detailed analyses to determine the effects of subtle changes in design or operating strategy. We are certain that we have not found the "best" designs nor fully optimized the designs investigated in detail. However, we do feel that these designs are representative of what "good" hybrid vehicles might be like in the future and can be used with reasonable confidence to assess the potential of HV's to become viable vehicle options.

In order to design and simulate the operation of hybrid and conventional vehicles with the necessary detail, the computer program "HYVEC" was developed. This program was equipped with the various component models desired for this study, including numerous heat engine maps, electric motor maps, and battery models as well as routines to determine weight propagation due to the added components.

#### A. GENERAL FINDINGS

Let us summarize the conclusions of the power train analysis by answering the following basic questions the analysis investigated:

- (1) Can hybrid vehicles reduce petro-fuel consumption at the vehicle level? How much?

Yes. Hybrid vehicles can reduce petro-fuel consumption at the vehicle-primarily by replacing petro-fuels with wall plug electricity. The amount of reduction is directly proportional to the size of the battery pack or (ratio of battery mass to gross vehicle mass) battery mass fraction.

- (2) Are hybrid vehicles only appropriate for some missions and not others?

No. Hybrid vehicles can be designed to displace significant amounts of petro-fuel on all the missions studied in this analysis.

(3) Must hybrid power trains be mission-specific?

No. Although some advantage can be gained by designing the power train to precisely fit the mission (and generally the driving cycle is the most important aspect of the mission in this regard) the gains are not very great. A hybrid vehicle of "general" design can do quite well on all the missions.

(4) Are advanced technologies required?

No. An adequate hybrid vehicle can be built using current technology although costs would be quite high. Advanced technologies can help reduce these costs considerably. Of particular interest are low cost, long life batteries, low cost controllers, continuously variable transmissions, and heat engines capable of frequent, rapid starts.

(5) Which hybrid power trains look the most promising?

The parallel hybrid with flywheel secondary storage looks the most promising in the long term. In the near term, however, the parallel system and operating strategy described in JPL Document 5030-345, Vol. II, is the most promising because it does not require development of a flywheel-transmission subsystem and associated controls. Series systems were found to be least desirable in general but may be a good choice for some special-purpose vehicles which were not considered in this study.

## B. SELECTION PROCESS

Early in the analysis it became obvious that detailed simulations of these vehicles would be required to make reasonably accurate comparisons with conventional vehicles, to decide among different hybrid systems which were indistinguishable at cruder levels of analysis, and to refine and optimize the designs finally chosen as "best". It was equally obvious that a general-purpose hybrid vehicle simulator was not available and could not be built within the time and budget allotted this task. Accordingly, a lengthy screening and selection process was performed to reduce the number of components and systems to a very few for detailed analysis.

A wide range of hybrid power train configurations is possible using various arrangements of batteries, motor/generators, generators,



controllers, flywheels, heat engines, transmissions, clutches and differentials. In addition a number of different types and designs of each component are available from which to select. Each type has characteristics which may be advantageous under certain circumstances.

Power train selection is further complicated by many operating control strategies for load sharing between the electrical and mechanical driveline components, and for charging the batteries when they reach a specified level of depletion.

Power train configurations can be separated into series, parallel and split configurations; and with or without secondary storage. A split configuration has completely separate drivelines for each system.

Primary storage energy units are those on which the range of the vehicle is dependent. The secondary storage units load-level the primary storage units by meeting peak power demands and storing energy during regenerative braking.

The following configurations were investigated in some detail:

- (1) Series with primary storage.
- (2) Series with primary and secondary storage.
- (3) Parallel with primary storage.
- (4) Parallel with primary and secondary storage.
- (5) Split with primary storage in each of the separate drivelines.

The following factors influence the over-all attractiveness of driveline configurations.

- (1) Weight
- (2) Cost
- (3) Mechanical/electric complexity
- (4) Adaptability to different driving cycles
- (5) Energy-use efficiency on electricity and petro-fuel

Selection criteria which were used for screening the various hybrid power train configurations included initial and operating costs, performance, safety and emissions. The designers also considered driveability, durability, and reliability.

A wide range of components, configurations, and operating strategies was analyzed and evaluated based on these criteria and the availability of performance data and math models (with the availability of performance maps a key driver). The following components were selected:

Heat engines:	Otto-cycle-reciprocating Diesel
Electric motor:	D.c. series--separately excited
Transmissions:	4-speed manual Continuously variable--for flywheel system
Batteries:	Advanced lead-acid Nickel-zinc Sodium-zulphur
Flywheel:	Composite

Three basic systems, a series, a parallel, and a parallel with flywheel secondary storage were simulated and are described in detail in JPL Document 5030-345, Vols. III, IV, and V. An overview of the power train analysis effort and a description of the simulation programs are presented in JPL Document 5030-345, Vol. IX. Not all systems were investigated for all missions, and operating strategies were modified continuously to improve fuel displacement. Unfortunately, neither the cost program nor the travel pattern program were available directly to the power train analysts until very late in the study so only one iteration could be made with detailed annual fuel consumption and life cycle cost data available. The results of the last iteration of the designs are described in the following paragraphs and in greater detail in JPL Document 5030-345, Vols. II through X.

The trade-offs investigated were basically the same for all systems with the exception of operating strategies, which differed significantly. Rather than discuss all three systems in this summary, the results of only the parallel system are presented in an abbreviated form and the reader is referred to JPL Document 5030-345, Vols. IV and V, for the discussions of the other systems.

#### C. PARALLEL HYBRIDS

This section deals with the parallel hybrid vehicle. This vehicle type is characterized by an arrangement of the heat engine and electric motor in the power-train such that a direct mechanical or fluid-mechanical power path from both the motor and engine to the

wheels is available. Out of the several possible component arrangements that could satisfy these requirements, a configuration in which the engine and motor are mounted in tandem, driving a 4-speed manual transmission, was selected for extensive computer analysis.

Simulation of all seven missions were run for this parallel hybrid configuration. The battery mass fraction (MFB), which is defined as the ratio of the battery mass to the gross vehicle weight (expressed in percent), was varied from 5% to 30% for each mission. These vehicles were designed such that the total energy usage of the battery before cut-off would be about 80% of the energy output of a constant power 3-h discharge rate (C/3 rate).

Due to the similarity of results for missions with similar acceleration and driving cycle requirements, Mission 2 (the four-passenger family runabout) and Mission 7 (a fixed-route delivery van) were selected for additional detailed trade-off studies. The reader is referred to JPL Document 5030-345, Vol. III for more detail.

#### 1. Fuel Economy

The major conclusions regarding fuel economy that can be drawn as a result of the analysis are: (1) petro-fuel consumption can be essentially eliminated or at least minimized during operation in the primary electric mode; (2) the petro-fuel consumption penalty of operating in the primary heat engine mode with increased vehicle weight (due to the added electrical system weight) can be minimized or eliminated by judicious sizing of the heat engine and motor.

#### 2. Battery Specific Energy and Specific Power

Increasing battery specific energy is very important up to a certain point, then the returns diminish due to the travel patterns, i.e., increasing a hybrid vehicles primary electric range from 60 to 80 km by increasing the specific energy of the battery pack by 30% is going to have a lesser effect on petroleum displacement because the frequency of travel between 60 and 80 km is lower than 40 to 60 km. Thus, somewhere between the specific energy available from lead-acid and sodium-sulphur batteries, a point of diminishing returns exists. This is not necessarily true for the electric vehicle, where the absolute range is determined by the specific energy.

The battery specific power and the associated energy trade-off is a more critical parameter. The specific power defines the minimum battery pack mass for a feasible vehicle design, and the overall costs are highly sensitive to the battery mass.

### 3. Design Considerations

Design optimization of parallel hybrid vehicles involves several important considerations and trade-offs. The most fundamental of these is the overall control strategy for the operation of the power-train. The basic strategy recommended as a result of this study for maximum petroleum displacement per dollar of life cycle cost is:

- (1) Maximum vehicle power requirements (which occur during the 0-100 km/h acceleration maneuver) are supplied by the heat engine and motor power applied simultaneously.
- (2) A major portion of electrical energy available in the batteries is used during the initial portion of the daily travel.
- (3) The heat engine is sized to supply all driving cycle power requirements for the FTP Urban and Highway cycles in the primary engine mode.
- (4) The electric motor is sized to supply the majority of driving cycle power requirements in the primary electric mode.
- (5) The heat engine is not used to charge the batteries, except after repeated maximum effort accelerations.
- (6) Batteries are normally not allowed to discharge below the point where they are capable of supplying peak motor power.

The major unresolved design consideration that is not included in the constraints is the optimum trade-off between battery discharge rate, total battery energy available, the size of the battery pack, and battery life. To answer this question, the overall costs of vehicle acquisition and operation must be included in the analysis.

The parallel hybrid configuration has several inherent design advantages over the series hybrid or the purely electric vehicle. Drive-train components can be sized and controlled such that the sum of the power produced is the maximum required by the vehicle, the range is limited only by the size of the fuel tank, and all of the power-producing components have a direct mechanical path to the wheels. The major disadvantage is the added complexity of the control system, which requires more detailed investigation but does not appear to be a particularly difficult problem.

A number of conclusions regarding design considerations can be drawn. Among these are:

- (1) Using the electrical energy to drive the vehicle at the beginning of the trip minimizes annual petro-fuel consumption.

- (2) Increasing the battery fraction increases annual petrofuel economy for mass fractions greater than 10%.
- (3) Engine on/off operation improves fuel economy over continuous-on operation by 6% to 15% for Missions 1, 2, 3, 5, and 6 when operating in the heat-engine-only mode. The effect is more striking for Missions 4 and 7 which have a higher proportion of idle time.
- (4) The reduction of the size of the heat engine and the concomitant increase in efficiency of the heat engine in normal operation offsets the weight penalty of the batteries and motor and allows the hybrid to have a fuel economy approximately equal to the conventional vehicle when operating in the heat engine mode.
- (5) The acceleration performance of the hybrid vehicle, particularly the parallel-flywheel hybrid vehicle, can be increased significantly with only a minor penalty in annual average fuel economy.

#### 4. Configurations

The configuration of the parallel hybrids discussed in this section is characterized as having a heat engine and a motor connected within the power train in such a way that each is able to supply power to the drive shaft and accessories either individually or simultaneously. Hybrid Configuration 1 features the motor and heat engine in a tandem arrangement, with the motor closest to the transmission, and clutches between engine/motor and motor/transmission. In this arrangement, the motor and engine shafts revolve at the same speed, and both power outputs flow through the transmission. A schematic diagram of Configuration 1 is shown in Figure 5-1. A number of other configurations were considered and investigated to varying levels of detail, and from an overall system performance point-of-view, many of these configurations are similar. However, all of the vehicles discussed in this section (Section C) were designed with Configuration 1.

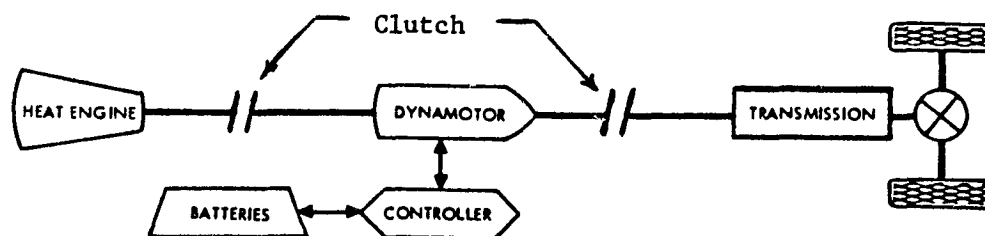


Figure 5-1. Parallel Hybrid Configuration 1

The conventional internal combustion engine (ICE) vehicle power train configuration modeled for baseline performance is shown schematically in Figure 5-2. The power train consists of a heat engine with accessories, a clutch, and a manual transmission.

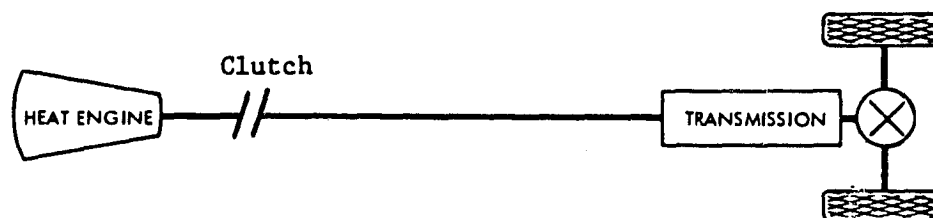


Figure 5-2. Conventional Power train

## 5. Control Strategies

The physical arrangements of the heat engine and electric motor in the hybrid parallel configurations allow considerable flexibility in determining the control strategy. The engine and motor can be operated individually at any point in time, or simultaneously. The decisions as to when and how much power should be supplied by each of the components as a function of parameters such as battery charge level and vehicle power requirements are made by the controller.

Although several control strategies were available within the HYVEC simulation program (see JPL Document 5030-345, Vol. IX) the principal control strategy used for the parallel configurations utilizes either the motor or the heat engine as the primary power source in the vehicle drive-train depending on the state-of-charge of the battery pack. The power train is then sized to meet the maximum acceleration performance requirements using the full power of the motor plus the full power of the heat engine. The operation of this strategy in the primary electric mode is illustrated in Figure 5-3 on a segment of the FTP Urban cycle. Operation in the primary heat engine mode would be considerably different, however, since the heat engine has sufficient power to meet all driving-cycle and most of the maximum acceleration power requirements by itself.

In addition to the primary control strategy outlined above, two other parallel hybrid control schemes were considered briefly in this analysis. The first of these is a modification of the principal strategy that eliminates the primary electric portion of the

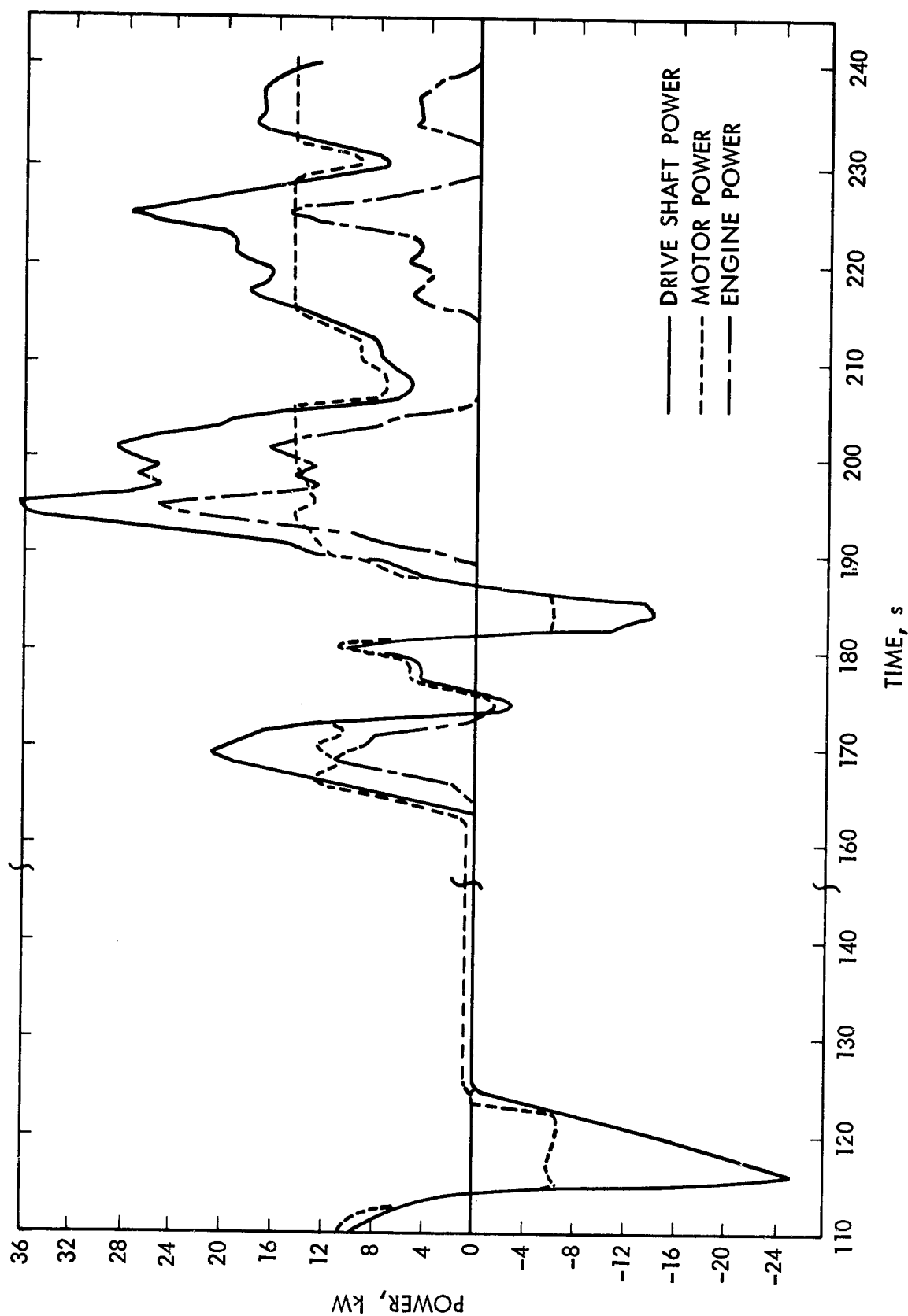


Figure 5-3. Power vs Time for Segment of FTP-Urban Cycle, Mission 2, Vehicle D, MFG = 10%, Lead-Acid

strategy. At the beginning of a trip, with batteries fully charged, the heat engine is the primary source of power. The electric motor is used to satisfy power requirements above the engines' maximum power capability. In this strategy, the engine may be arbitrarily limited to a given percentage of actual maximum power, in an attempt to eliminate operation at unfavorable efficiency points. This control strategy is commonly called heat-engine load leveling.

The last control strategy is similar to the principal strategy except the criterion for switching from electric mode to heat engine mode is not based upon the battery state-of-charge, but upon the vehicle velocity.

These secondary control strategies were both considered in several cases for Mission 2. The primary heat engine strategy was rejected due to the high fuel consumption in the initial portion of the trip, and negligible difference in overall fuel economy. The strategy utilizing vehicle velocity as the determinant for transition from electric to heat engine mode was rejected due to the undesirability of frequent on and off heat engine operation.

The baseline ICE vehicle is controlled conventionally. Regenerative braking is utilized in the hybrid vehicle down to a preselected minimum vehicle speed, usually around 10 km/h.



## SECTION VI

### COST ANALYSIS

The purpose of the cost analysis was to determine the economic feasibility of a variety of hybrid vehicles with respect to conventional vehicles specifically designed for the same mission. Because this task was a potential assessment rather than a market projection and because we did not want to become deeply involved in market analysis, the surrogate chosen for economic feasibility was the break-even gasoline price (BEGP). The break-even gasoline price is that price where the life cycle cost of the hybrid vehicle equals that of the conventional vehicle (in 1978 dollars). Although commercial vehicle buyers commonly purchase on the basis of life cycle cost, there is no evidence to show that the average consumer uses this criterion. In short, if the consumer evaluated a vehicle purchase based on the costs incurred over the vehicle life, then the BEGP would be a reasonable estimate of economic feasibility. The assumption has been made that the hybrid vehicles have the potential to penetrate a market when the BEGP is less than the projected gasoline price (See Section VII for penetration scenarios and impacts) and thus becomes more cost effective than its conventional competition.

This study evaluated several different hybrid configurations including parallel, parallel-flywheel, and series vehicles which had been designed with the same minimum performance requirements as well as the same passenger and payload capability within each mission as described in Section V. The first step in the cost analysis was to apply the travel patterns determined by the mission analysis to the vehicle designs to determine annual energy consumption, battery life, and vehicle life. The next step was to apply the EHV Cost Handbook (JPL Document 5030-345, Vol. X) to the vehicle specifications and energy consumption information to determine life cycle costs (manufacturing costs, purchase price, operating costs) as well as the BEGP. The flow diagram of Figure 6-1 will aid the reader in understanding the costing procedure.

This study also investigated the ramifications of incorporating examples of advanced batteries into hybrid vehicles, these being the "advanced" lead-acid, nickel-zinc, and sodium sulfur. Vehicles were specifically designed for these batteries and the driving cycles specified by the mission.

#### A. GENERAL FINDINGS

The conclusions from the cost analysis can be summarized by answering the following working questions employed in this analysis:

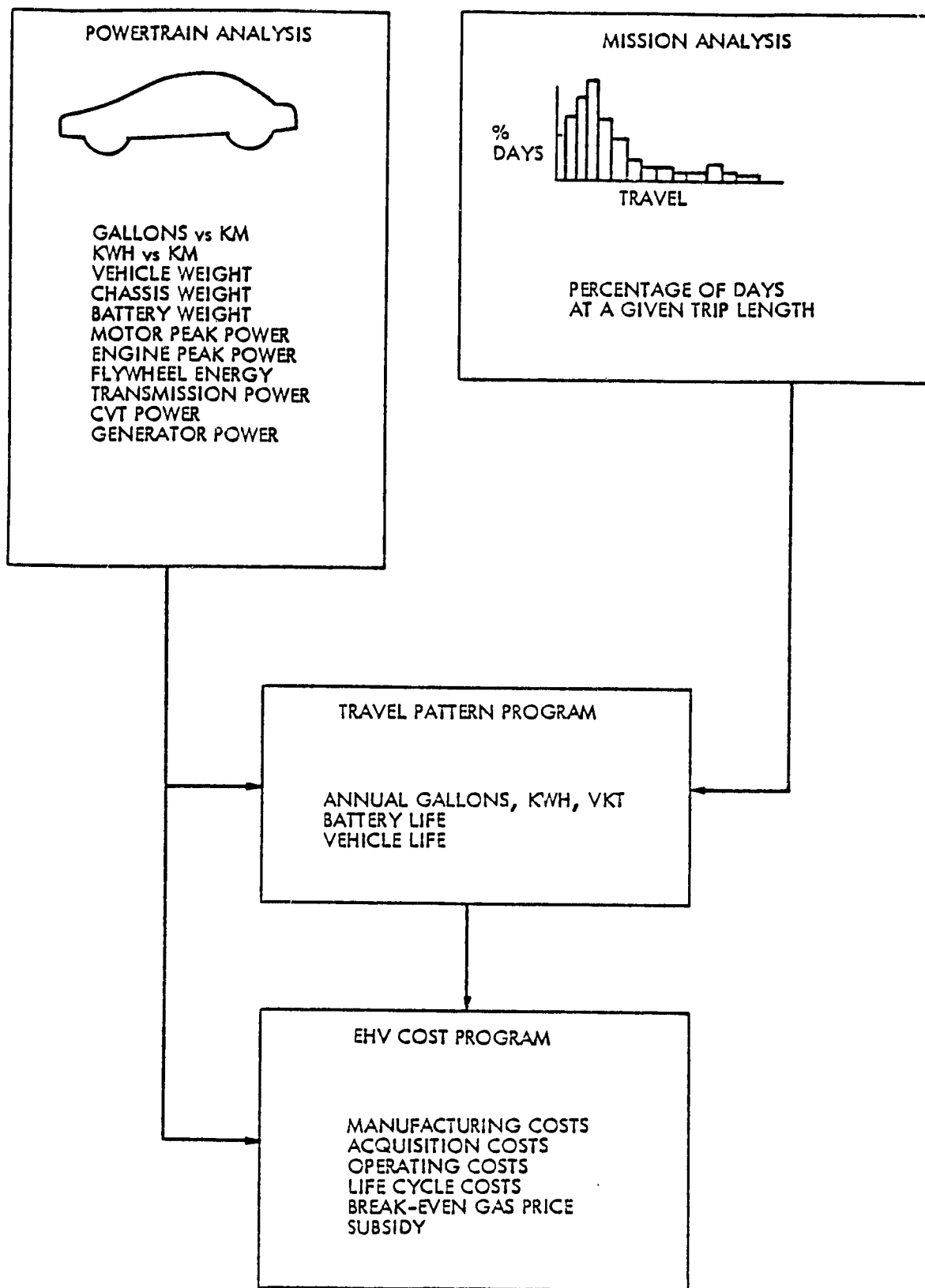


Figure 6-1. Cost Analysis Flow Diagram

- (1) When will hybrid vehicles become cost competitive at least on a life cycle basis for the general public?

In the event that gasoline prices reach \$2.00 to \$3.00/gal (depending on the HVs electric range and technology advances) and all other components of vehicle costs remain the same (in 1978 dollars), hybrid passenger cars (representing a large percentage of the fleet) will become cost competitive with conventional vehicles.

- (2) When will hybrid vehicles become attractive to the commercial purchaser?

In some commercial applications it appears that hybrid vehicles will be cost competitive somewhat earlier than private vehicles, when the gasoline price ranges from \$1.20 to \$1.50/gal (1978 dollars) if sufficient numbers of such vehicles can be sold to achieve economies of scale.

- (3) How do the various hybrid vehicle designs compare in terms of cost?

The series hybrid vehicles were found to be relatively expensive in comparison to the parallel or parallel-flywheel hybrids.

- (4) What are the main "cost-drivers" in the hybrid vehicles?

The major contributor to the high BEGP was the cost of batteries.

- (5) How do the advanced batteries affect the hybrid vehicle cost situation?

The vehicles designed with the nickel-zinc and sodium-sulfur batteries were more expensive than the advanced lead-acid vehicles, that is, the BEGPs were higher. The high cost per kilowatt hour or low cycle life of the advanced batteries outweigh the cost benefits that accrue due to higher specific energy and specific power.

The DOE battery R&D program cost and cycle life goals were used in this part of the analysis. If the nickel-zinc or sodium-sulfur batteries exceed those goals then this conclusion could change. With 20/20 hindsight it is unfortunate that we did not include nickel-iron batteries in the analysis as their cost and cycle life look very attractive.

## B. COSTING METHODOLOGY

A computer program was developed to apply the travel patterns to each basic vehicle design which resulted from the power train analysis. This program produced annual kilometers per liter, kilowatt-hours per kilometer, and vehicle kilometers travelled (VKT). Another function of the travel pattern program was to determine the battery life based on the particular driving pattern and the battery cycle life. The cycle lives were treated parametrically. Cycle lives of 500 and 1000 were chosen to represent basically current technology and the design goals for the 1985-1990 time period. A third cycle life of 2000 was chosen to show the effects on cost if this admittedly optimistic lifetime were achieved.

### 1. Vehicle Design

The most basic assumptions inherent in the comparative cost analysis concern the vehicle design. The vehicles have been designed with identical minimum performance requirements as well as passenger and payload capability. The technical aspects of all vehicles within the same mission are also identical (i.e., frontal area, drag coefficient, rolling resistance coefficients, baseline carriage weight, etc.).

The hybrid vehicles were designed with several "primary electric" ranges to show the effect of fuel displacement on overall costs. The definition of "electric range" differs somewhat for each vehicle design and operating strategy. In an effort to be conservative in terms of battery life, the primary electric range was defined for the cost analysis as that distance where the battery reached an 80% depth of discharge (DoD) at a 3-h discharge rate (C/3).

### 2. Battery Life

The travel pattern program has been designed to transform energy consumption, which is supplied at given intervals of distance traveled from start with a fully charged battery, into an annual average kilometers per liter and kilowatt-hours per kilometer by applying a particular trip length distribution. By using this same distribution, the lives of the batteries were calculated under the assumption that batteries have a total limited number of kilowatt hours they can supply in their lifetime (i.e., a battery regularly discharged 40% lasts twice as long as one regularly discharged to an 80% DOD).

### 3. EHV Cost Handbook

The purpose of the EHV Cost Handbook (JPL Document 5030-345, Vol. X) is to provide a consistent set of cost estimating relationships (CERs) for determining the manufacturing, acquisition, operating, and life cycle costs for electric and hybrid vehicles. Furthermore, the cost data is presented for major component and sub-assembly costs so that conventional vehicles as well can be costed under the same basic assumptions. However, since no consistency exists among the various sources used in compiling the handbook in the definitions of manufacturing cost, the assumptions used, or the level of effort expended, the range of estimates is very large. For this reason the handbook should be used in a comparative, not absolute manner.

There are a number of important assumptions inherent in the Cost Handbook and these are described in JPL Document 5030-345, Vol. VI.

The EHV Cost Handbook was used to translate the technical aspects and energy consumption of these vehicles into cost data. Based on the common design criteria and set of cost estimating relationships, a comparative cost analysis was performed using discounted present value of life cycle costs.

The original intent was to find a set of HV design/mission combinations with lower life cycle costs than conventional vehicles, project their impacts on national petro-fuel consumption, and recommend the design/mission set that produced the largest reduction in petro-fuel consumption for system R&D and possible introduction into the Demonstration Program. None could be found with lower life cycle costs at current gasoline prices or our projected 1985 gasoline price of \$1.05/gal (which now, in the summer of 1979, looks very low).

In order to determine how far away each vehicle was from becoming cost-competitive, the break-even gasoline price was calculated for each vehicle. Because the BEGP was found to be higher in all cases than the expected price of gasoline in 1985, the subsidy or reduction in purchase price necessary to make the hybrid vehicle competitive was also calculated.

Because the cost of batteries has such a strong influence on the total cost of hybrid vehicles, the assumptions for the batteries investigated are listed in Table 6-1.

The cost program outputs all aspects of cost of a particular vehicle including manufacturing costs, maintenance, repair, etc. With the cost information for the conventional vehicles built into the program, comparative cost analysis is automatically performed for vehicles of the same mission.

Table 6-1. Battery Cost and Energy Assumptions

	Advanced Lead-Acid	Sodium- Sulfur	Nickel- Zinc
Specific Energy	44 Wh/kg	120 Wh/kg	77 Wh/kg
Manufacturing Cost	\$40/kWh \$1.76/kg	\$50/kWh \$6.00/kg	\$60/kWh \$4.62/kg
Purchase Price	\$80/kWh \$3.52/kg	\$100/kWh \$12.00/kg	\$120/kWh \$9.24/kg
Replacement Price	\$92/kWh \$4.05/kg	\$115/kWh \$13.80/kg	\$138/kWh \$10.63/kg

### C. FUEL DISPLACEMENT TRADE-OFFS

At the outset of the cost analysis, it was expected that life cycle costs, BEGP, or other overall measures would tend to show minimums for most vehicle design/mission combinations where the primary electric range (i.e., battery pack size) best matched the travel pattern. In general this is the case, but the minimums tend to be very wide and flat and near the minimum battery pack size required for most designs. The effect is to produce a trade-off between life cycle cost and its components and fuel displacement at any given gasoline price. The more fuel displacement desired, the larger the battery pack required and, hence, the higher the acquisition and life cycle cost.

These trade-offs are extremely similar for all the missions and even quantitatively very close for Missions 1, 2, and 3. Examples of these tradeoffs for Mission 2 (low annual AVKT) are summarized in the brief discussions which follow.

#### 1. Acquisition Cost Ratio vs Fuel Displacement

One dominant economic factor concerning the hybrid vehicles is the higher initial cost relative to conventional vehicles designed for the same mission. Since the private individual does not generally buy a vehicle based on projected life cycle cost at the present time, this could be a very important factor in sales. The purchase price ratio for Mission 2 vehicles ranged from 1.1 to 1.75 as shown in Figure 6-2. It can be seen that the battery type had little effect on the purchase price for vehicles designed for the same mission.

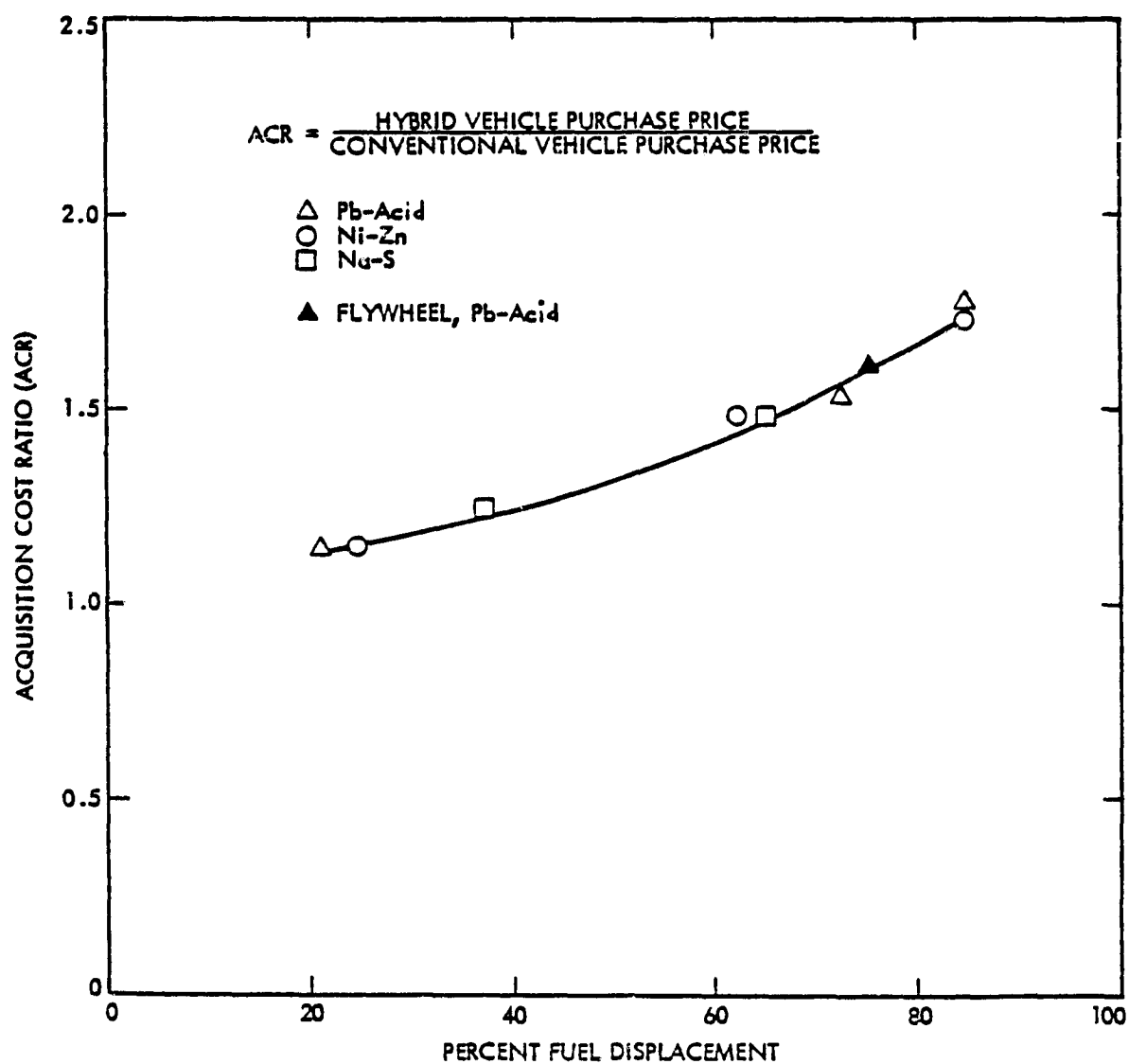


Figure 6-2. Mission 2 Acquisition Cost Ratio

## 2. Operating Cost Ratio vs Fuel Displacement

Since the hybrid vehicles have a higher projected acquisition cost, they must be capable of saving operating cost to become economically competitive. However, with gasoline prices projected as high as \$1.30/gal the hybrid vehicles still cannot save operating costs as can be seen in the example of Figure 6-3.

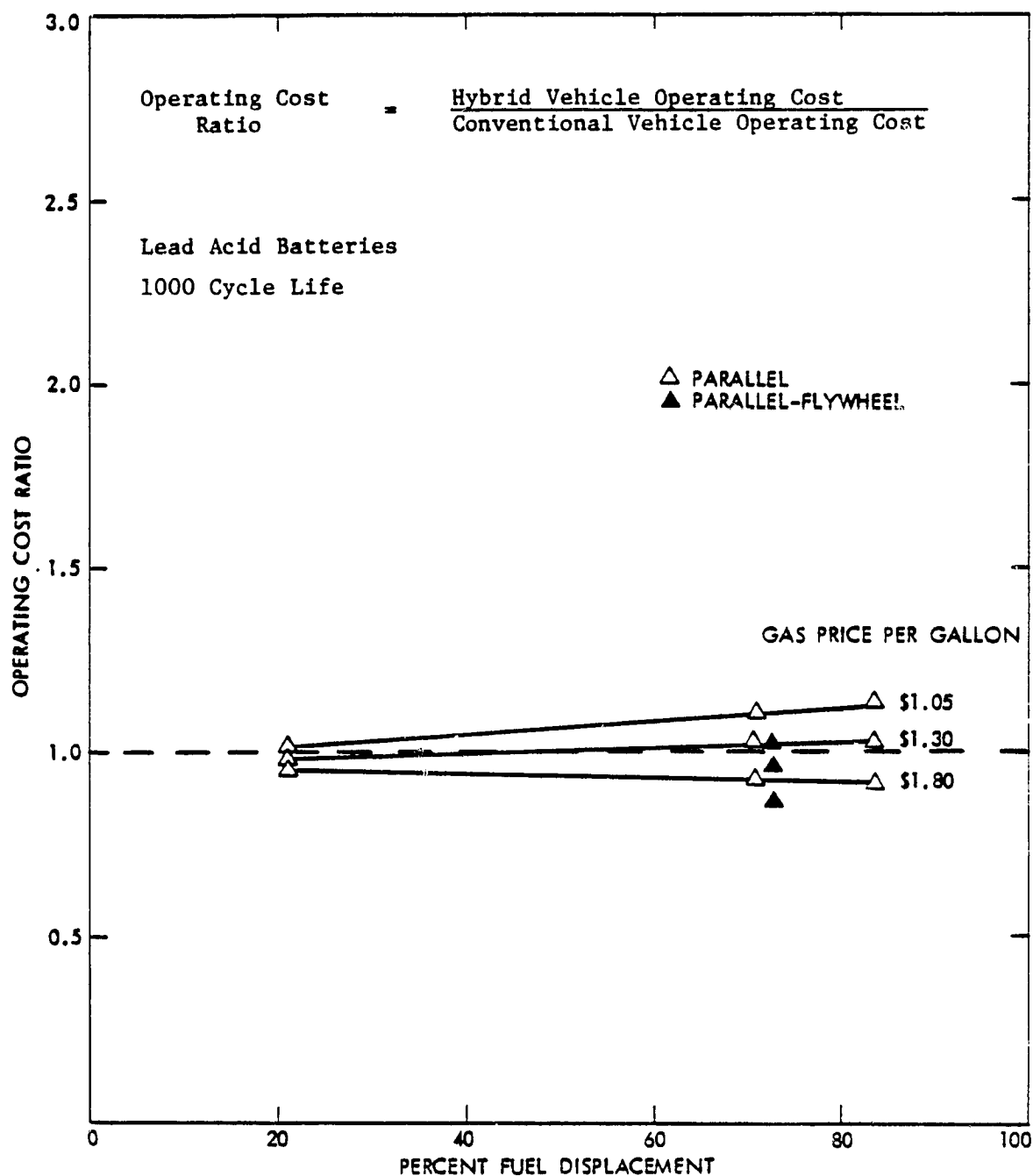


Figure 6-3. Mission 2 Operating Cost Ratio



### 3. Life Cycle Cost vs Fuel Displacement

The life cycle cost increases with fuel displacement due primarily to the additional purchase price and the related costs of financing, tax, license, and insurance.

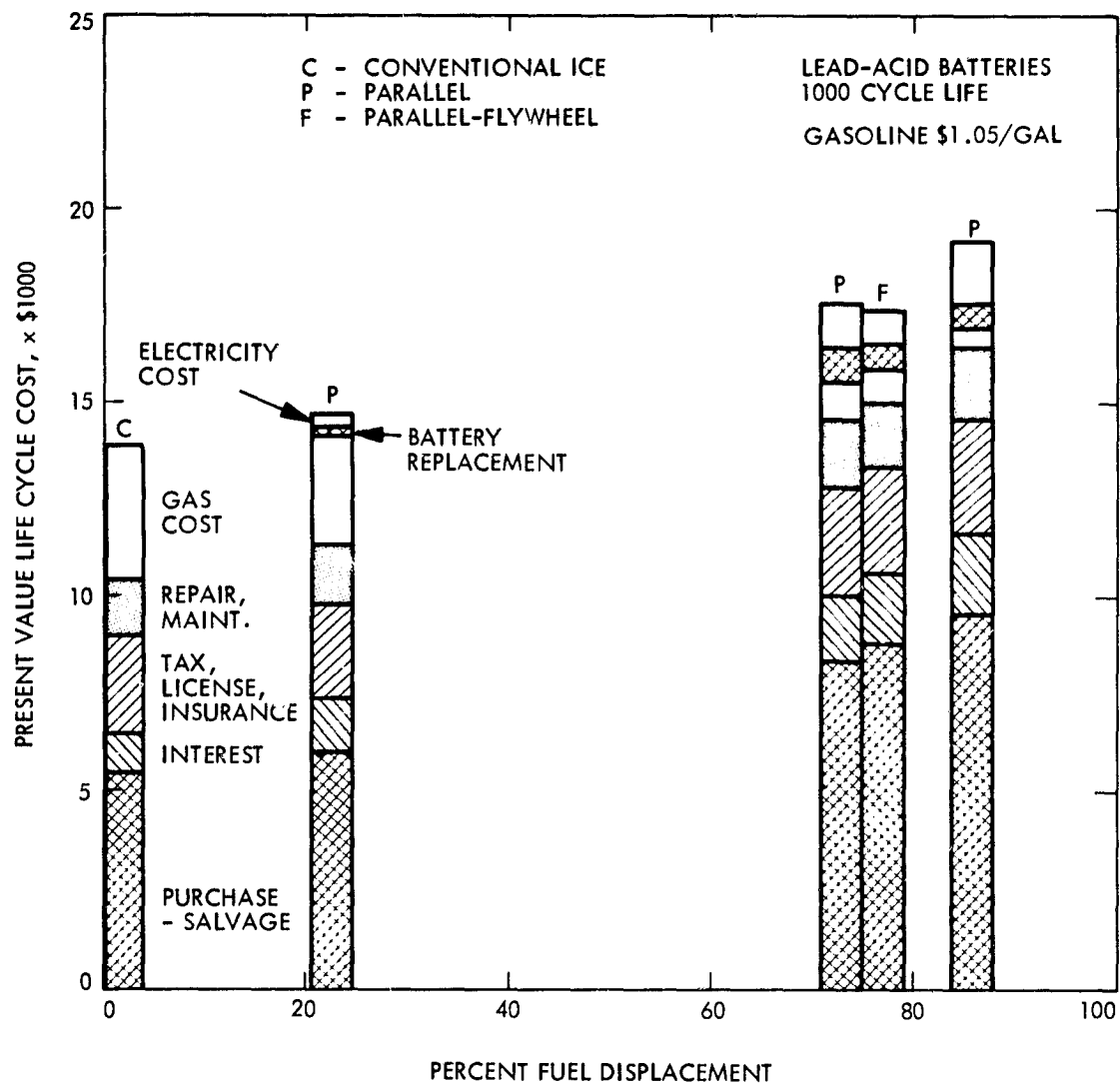


Figure 6-4. Mission 2 Life Cycle Cost

#### 4. Break-Even Gasoline Price vs Fuel Displacement

The passenger cars with the minimum BEGP were those designed for low fuel displacement. Figure 6-5 shows the minimum at approximately \$2.00/gal for 2000 cycle life lead-acid batteries. This level was prevalent throughout the private vehicle missions. Figure 6-6 presents the component breakdown of the BEGP. It can be seen from Figure 6-6 that battery costs (initial and replacement) are the dominant cost factors, but electricity, controller, and interest charges also contribute significantly.

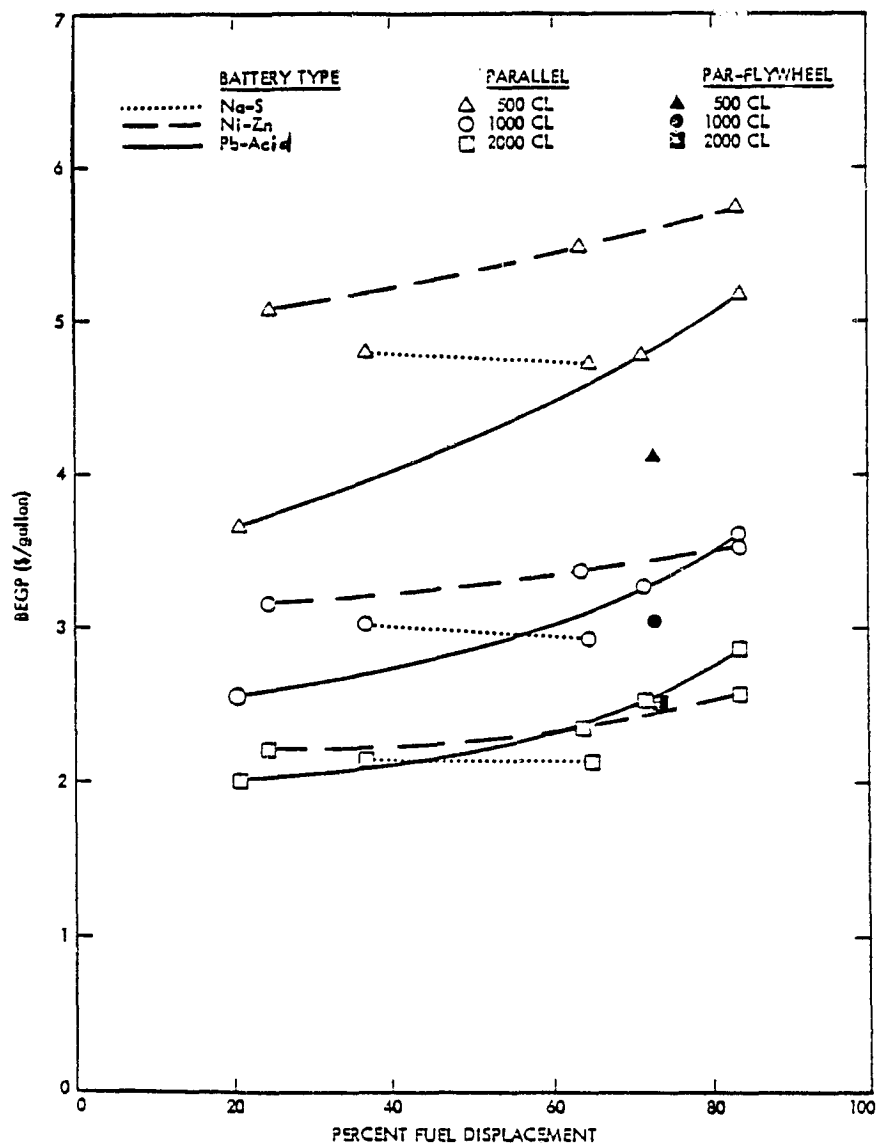


Figure 6-5. Mission 2-1 Break-Even Gasoline Price

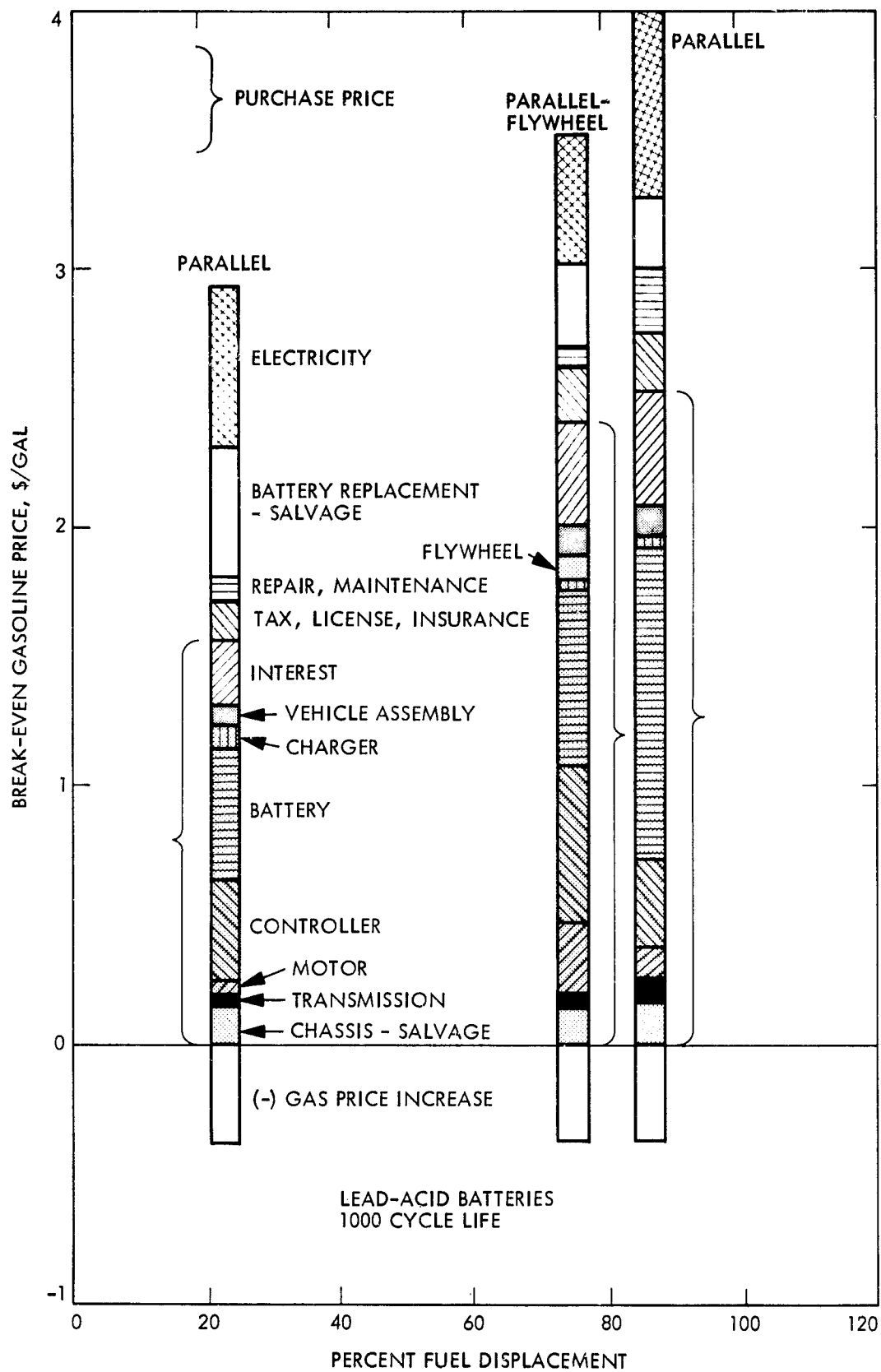


Figure 6-6. Mission 2-1 Comparative BEGP Cost Breakdown

## 5. Battery Cost Requirements vs Fuel Displacement

The batteries have been identified as the dominant cost factor in hybrid vehicles. However, it appears that reduction in battery cost alone will not be enough to make the hybrid passenger car cost competitive for some time to come. Figure 6-7 presents the required battery purchase price in dollars per kilowatt-hours per cycle necessary to achieve equivalent life cycle cost with ICE vehicles at various gasoline prices

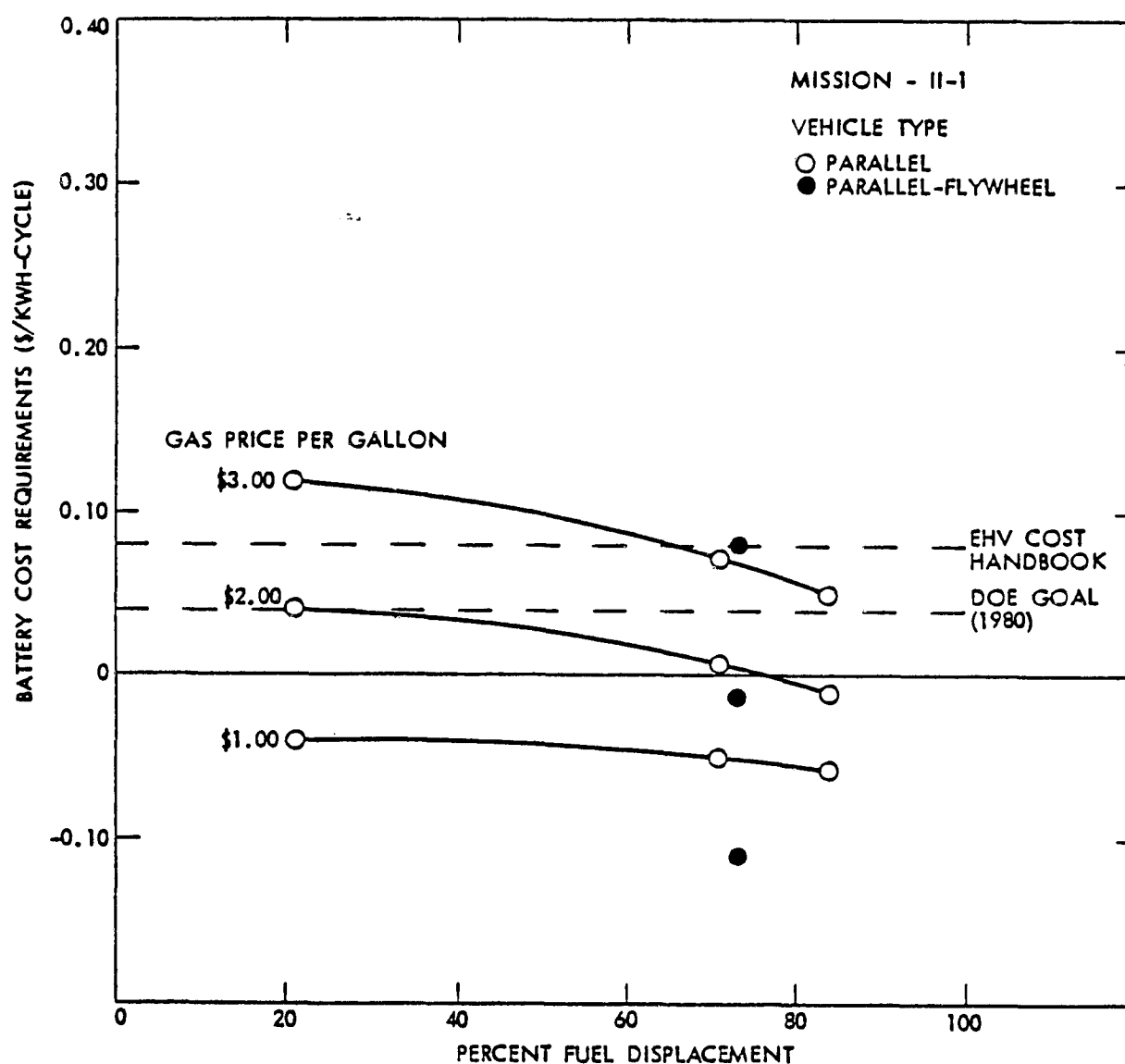


Figure 6-7. Lead-Acid Battery Purchase Price Requirements for Equivalent Vehicle Life Cycle Cost

## SECTION VII

### HYBRID VEHICLE IMPACTS ON PETROLEUM CONSUMPTION

The primary concern of this study was to evaluate the feasibility and the potential impact on national petroleum consumption of hybrid vehicles as a substitute for conventional ICE vehicles.

The assessment of the potential impacts of hybrid vehicles on national petroleum consumption, which is the focus of this chapter, was performed by applying the results of the mission, the powertrain, and the cost analysis to a limited number of scenarios. The scenarios were chosen to represent a variety of situations by varying the level of battery technology and gasoline price increases, and other variables such as number of vehicles, vehicle kilometers travelled, and so on. Since subsidization of EHV's is frequently suggested as a means of accelerating their introduction and impact, several levels of subsidy were introduced into the analysis to determine their impact on these scenarios. The basic elements of these scenarios are describe in Subsection B of this Section.

As discussed in Section II, the basic assumption used to estimate the potential impact of hybrid vehicles was that an HV could begin to penetrate its appropriate market segment as soon as its life cycle cost was lower than its competitors--conventional vehicles and other HVs. However, there is no data that we are aware of to indicate that any large group of American vehicle buyers actually use life cycle cost as a purchase criterion. While this basic assumption is of questionable validity, it does represent a possible upper bound on the market penetration of HVs.

#### A. GENERAL FINDINGS

The conclusions from the petroleum impact analysis can be summarized by the answers obtained to the following working questions:

- (1) Will hybrid vehicles penetrate the vehicle market and impact the petroleum consumption of the U.S. vehicle fleet with current levels of technology and gasoline prices?

Hybrid vehicles will have very little or no penetration or impact on the annual petroleum consumption in the two baseline scenarios (Scenarios A0 and B) where:

- (a) The cycle-life of the advanced batteries considered in this study (lead-acid, nickel-zinc, and sodium-sulfur) does not improve beyond 1000 cycles, and

- (b) No subsidy is offered to the new HV car and light truck buyers, and
  - (c) The gasoline price stays below \$2.00/gal.
- (2) What conditions are necessary for hybrid vehicles to impact petroleum consumption substantially?

A considerable amount of petroleum could be saved both annually and cumulatively before the year 2010 through the introduction of hybrid vehicles if any of the three factors above were to increase to:

- (a) 2000 cycles for lead-acid batteries in 1995 (Scenario A1, see p. 7-5), or
  - (b) \$1000-1500 in subsidy of each new hybrid vehicle purchase (Scenario A2 and A3), or
  - (c) \$3.00/gal gasoline price by the year 2000 (Scenario A4).
- (3) What is the optimistic potential of hybrid vehicles in terms of market penetration and petroleum impacts?

The three scenarios (A2, A3, and A4) generate an almost equal hybrid vehicle market penetration by year 2010 of about 75% of the total fleet, however their annual petroleum savings in year 2010 vary from 3.5 to 4.6 quads out of 9 quads projected under Scenario A.

- (4) What is the maximum potential of hybrid vehicles in terms of petroleum impacts?

If the nation wishes to pay the price, hybrid vehicles could be used to replace 80% of the petroleum used by cars and light trucks with electricity by the year 2010.

## B. SCENARIOS

A total of six scenarios were developed in order to reflect a reasonable range of possible futures. Two of these scenarios, the baseline Scenarios A0 and B, are outlined in detail in the JPL Document 5030-345, Vol. VIII. The projected fleet size, average annual vehicle kilometers traveled (AVKT), and gasoline price for Scenarios A and B are summarized in Figures 7-1, 7-2, and 7-3.

A total of 17 market sectors were defined in the scenario generation process, each of them with a specific average AVKT and

percent market share. Fifteen of these market sectors were specified through the mission analysis (see Chapter 3) to represent an array of typical travel patterns for passenger cars (11 sectors) and light trucks (4 sectors). The mission analysis also concluded that these 15 travel patterns (market sectors) together would represent about 90% of the total passenger car fleet and 45 percent of the total light truck fleet. Two more market sectors, labelled "other cars" and "other light trucks", were therefore added to these 15 sectors so that the 17 market sectors together would be representative of the whole passenger car and light truck fleet.

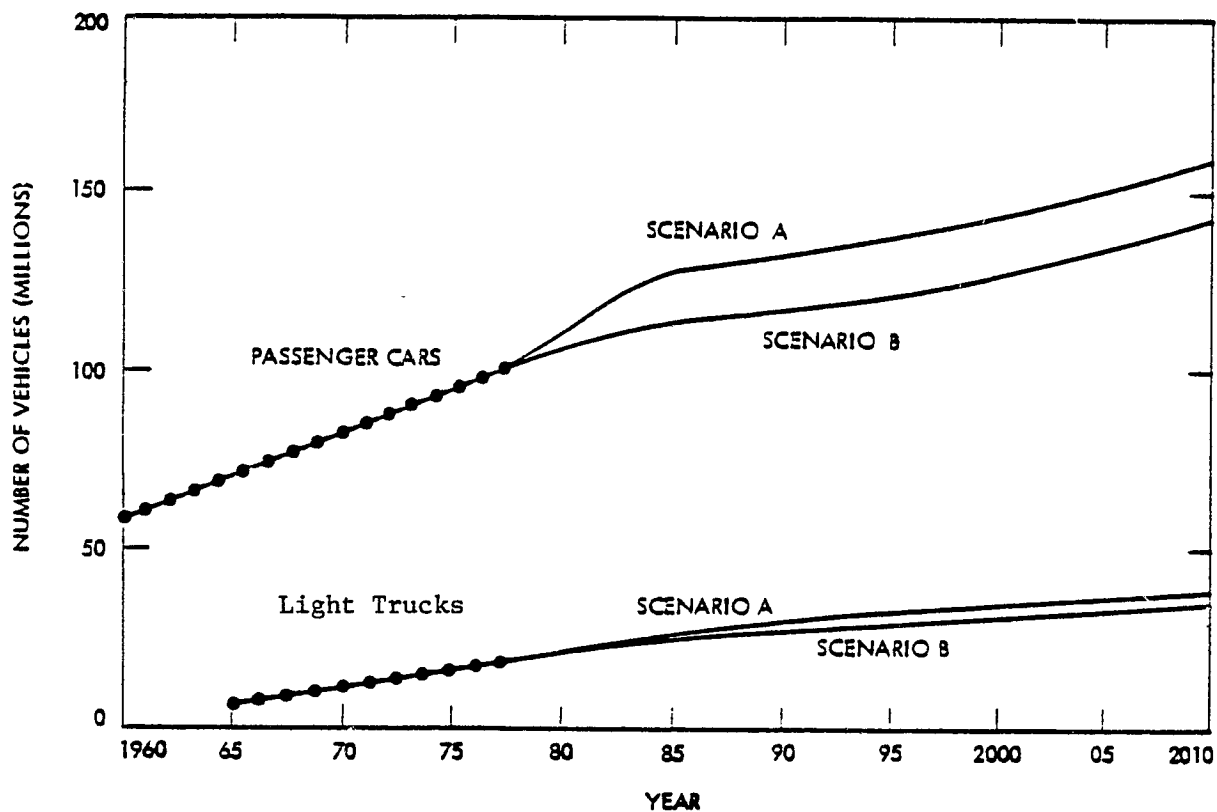


Figure 7-1. Passenger Car and Light Truck Fleet Size Scenarios

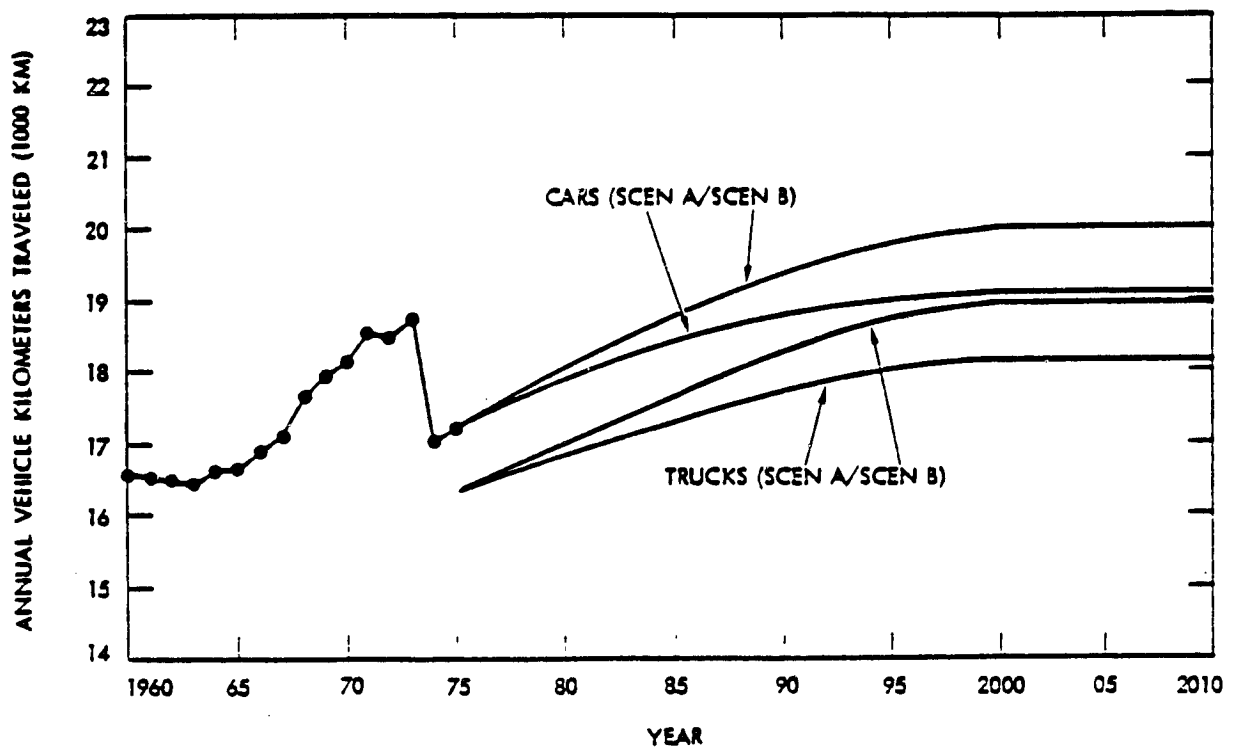


Figure 7-2. Fleet Average AVKT Scenarios

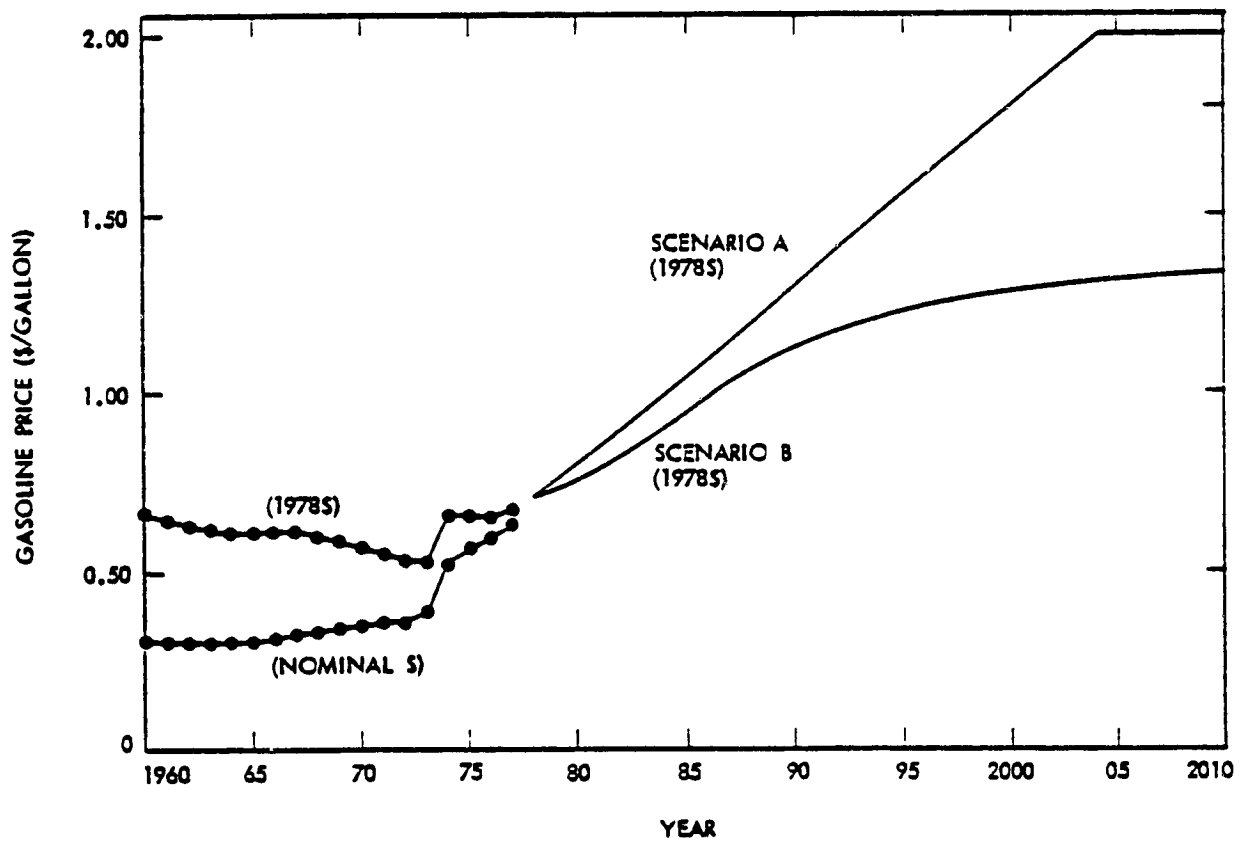


Figure 7-3. Gasoline Price Scenarios



A moving ICE base case was generated assuming no hybrid vehicle market penetration. The projected fleet fuel economies (identical for Scenarios A and B) and the resulting annual petroleum consumption rates for the ICE baseline are summarized in Figures 7-4 and 7-5

With the moving baseline ICE vehicle scenarios in hand, six hybrid impact scenarios were developed from Scenarios A and B with varying assumptions about battery development, purchase price subsidies, and gasoline prices. The battery technologies assumed for all scenarios are shown in Table 7-1.

Table 7-1. Battery Cycle Life Scenarios

Cycle Life	Lead-Acid		Nickel- Zinc	Sodium- Sulfur
Scenario A1				
1980	500	500	N/A <sup>a</sup>	N/A
1985	1000	1000	500	N/A
1990			1000	N/A
1995		2000		1000
2000				
2005				
2010	1000	2000	1000	1000

<sup>a</sup>Not available to manufacturers

The six scenarios were specified as follows:

(A0): Scenario A, with no subsidy of HVs

(A1): Scenario A, with a 2000 cycle-life lead-acid battery available in the year 1995.

(A2): Scenario A, with a \$1000 maximum subsidy of new HVs.

(A3): Scenario A, with a \$1500 maximum subsidy of new HVs

(A4): Scenario A, with a modified gasoline price scenario which increases gasoline prices by \$0.10/yr from 1980 to \$3.00/gal in the year 2002 and then remains at \$3.00/gal to 2010 and no subsidies of HVs

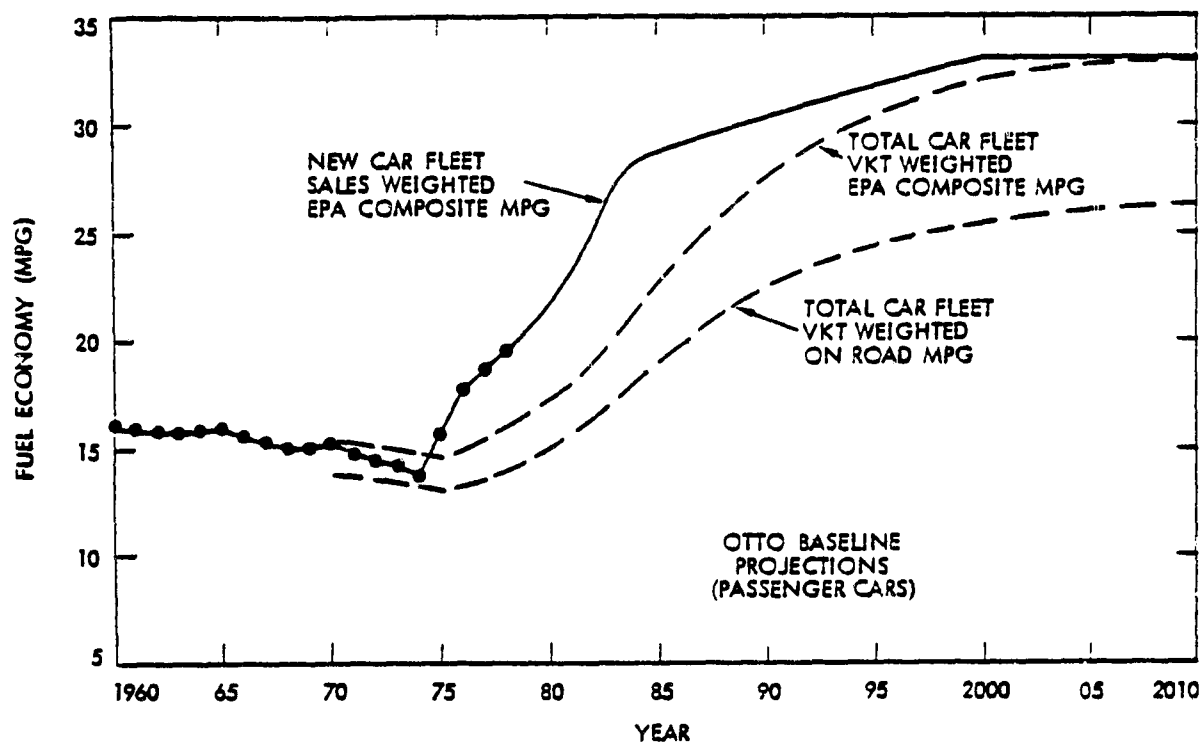


Figure 7-4. Fleet Fuel Economy Scenarios (ICE Baseline)

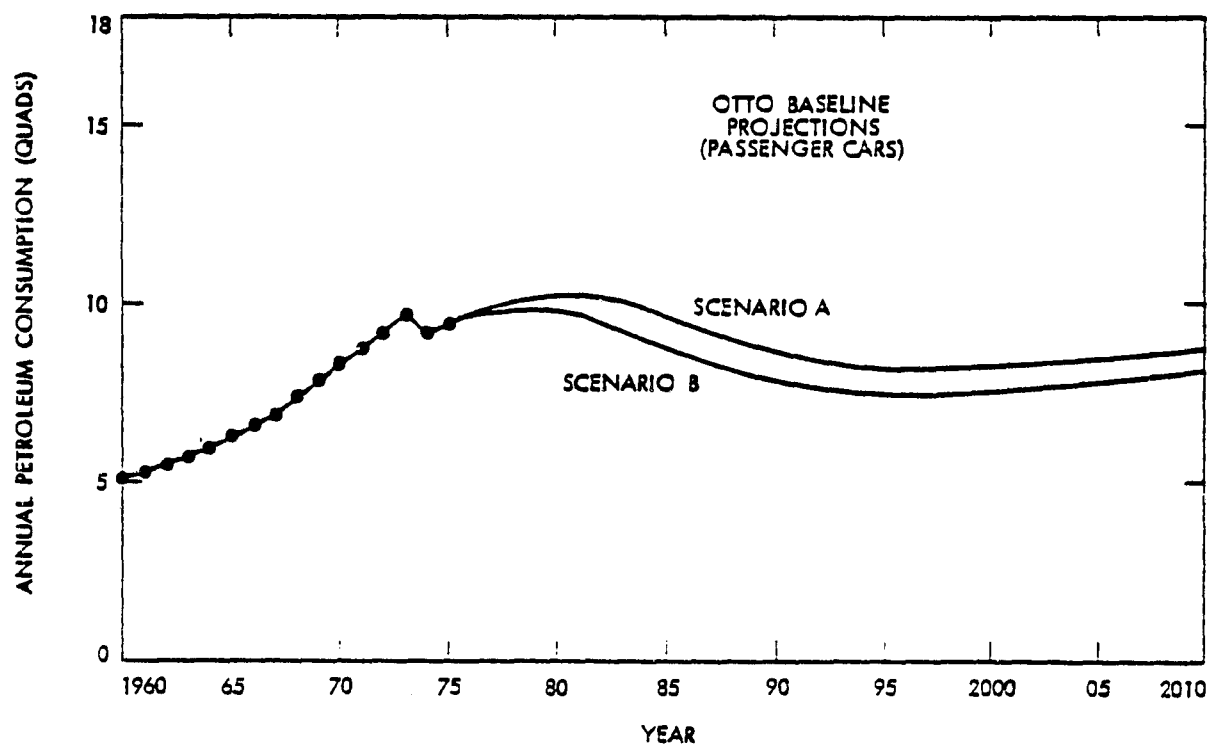


Figure 7-5. Annual Petroleum Consumption Scenarios (ICE Baseline)

(B0): Scenario B, with no subsidies of HVs.

Under the constraints of these scenarios, dramatic increases in the on-road fuel economy for new vehicles are possible with the introduction of hybrid vehicles. For instance, the most optimistic scenario in terms of fuel economy would raise the new car fleet miles per gallon by approximately 100% as shown in Figure 7-6.

The hybrid vehicle market penetration levels necessary for the fuel economy increases are shown with respect to the specific scenarios in Figure 7-7. The S-curve penetrations approach an asymptote of 75% of the vehicle fleet by the year 2010.

The resulting annual and cumulative petroleum displacements are shown in Figure 7-8 and 7-9.

The effect of hybrid vehicles on the U.S. vehicle fleet mix and associated energy consumption can be summed up quite briefly as follows:

Under some of the scenarios presented in this study, hybrid vehicles have the potential to penetrate the market quite heavily and displace a significant amount of the petroleum used for transportation. However, this potential is unlikely to be realized unless hybrid vehicles are subsidized in some form or gasoline prices rise dramatically. Another possibility, which is much more difficult to analyze, is that the buying public might place a high monetary value on the intangible benefits of the hybrid vehicles such as their multifuel capability or clean, quiet operation in electric mode, and totally ignore their cost disadvantages. Recent events in the spring and summer of 1979 have demonstrated that many people will take extreme measures to guarantee their personal mobility.

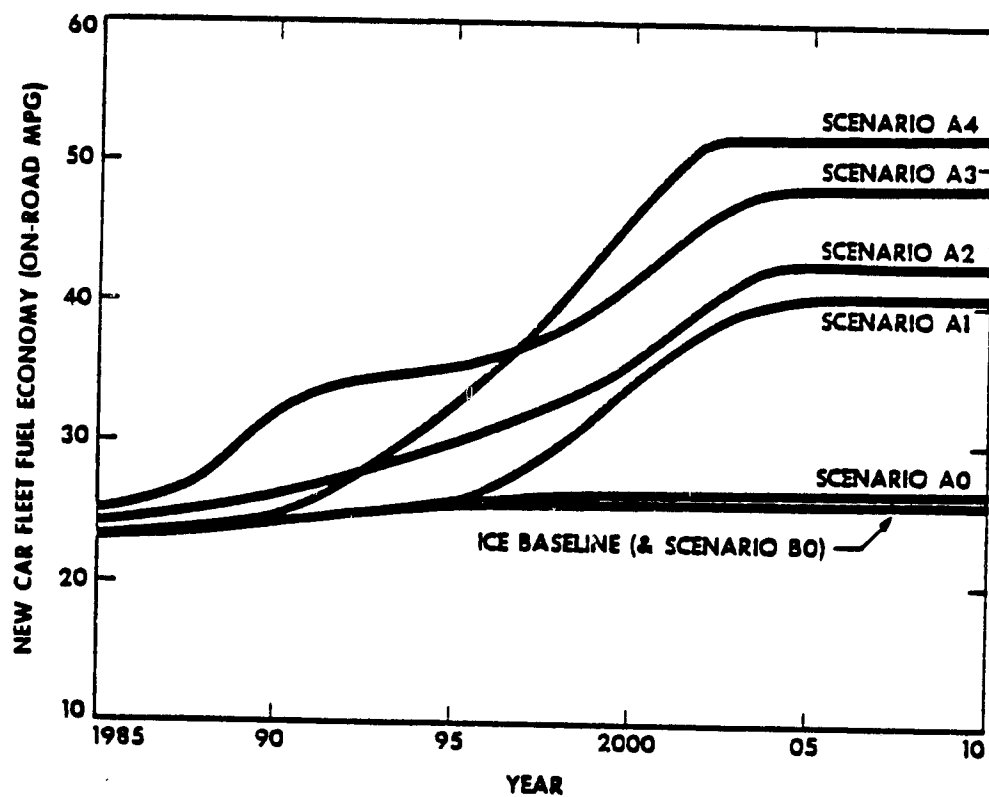


Figure 7-6. New Car Fleet Fuel Economy with Hybrid Vehicle Market Penetration

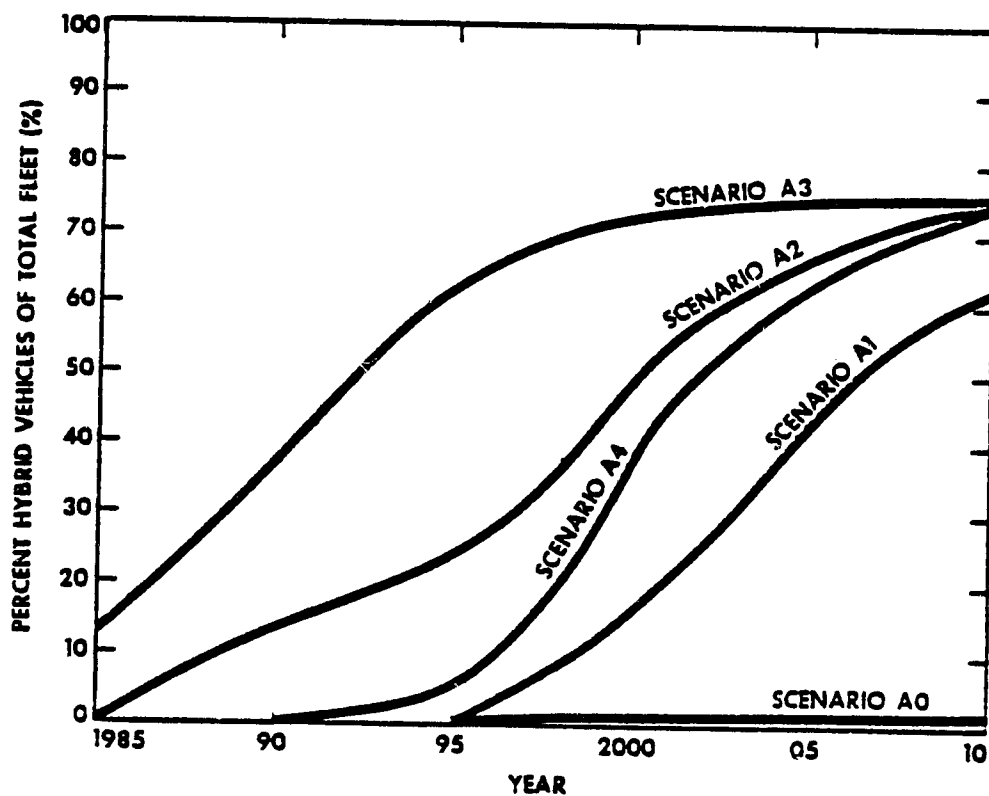


Figure 7-7. Hybrid Vehicle Market Penetration

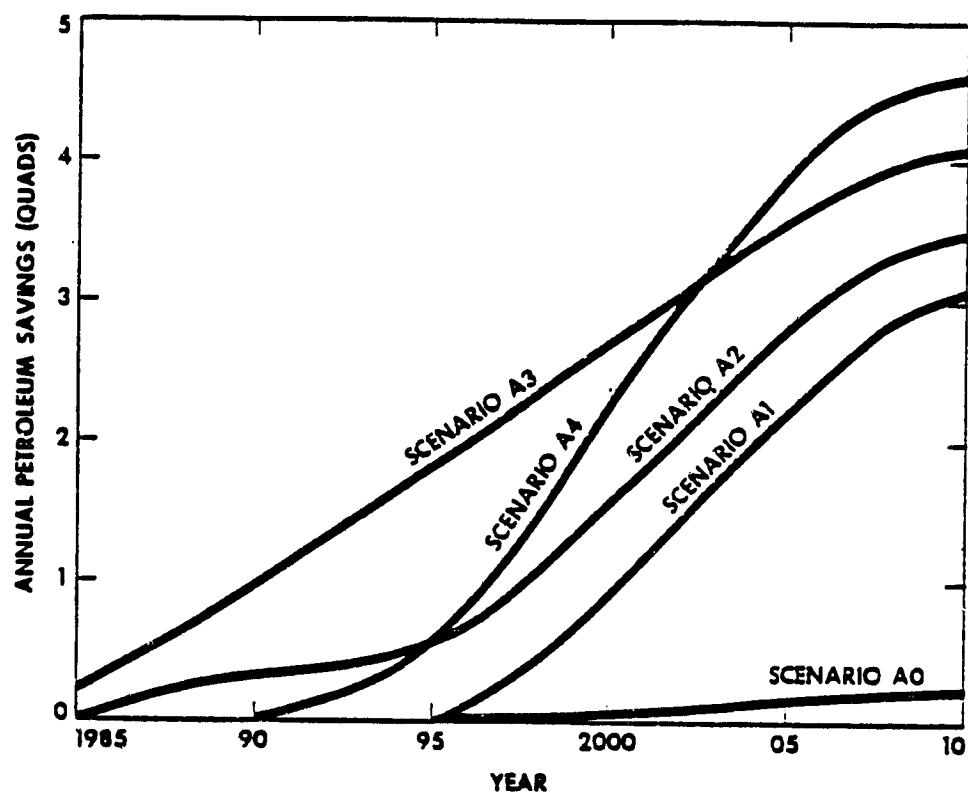


Figure 7-8. Annual Petroleum Savings with Hybrid Vehicles

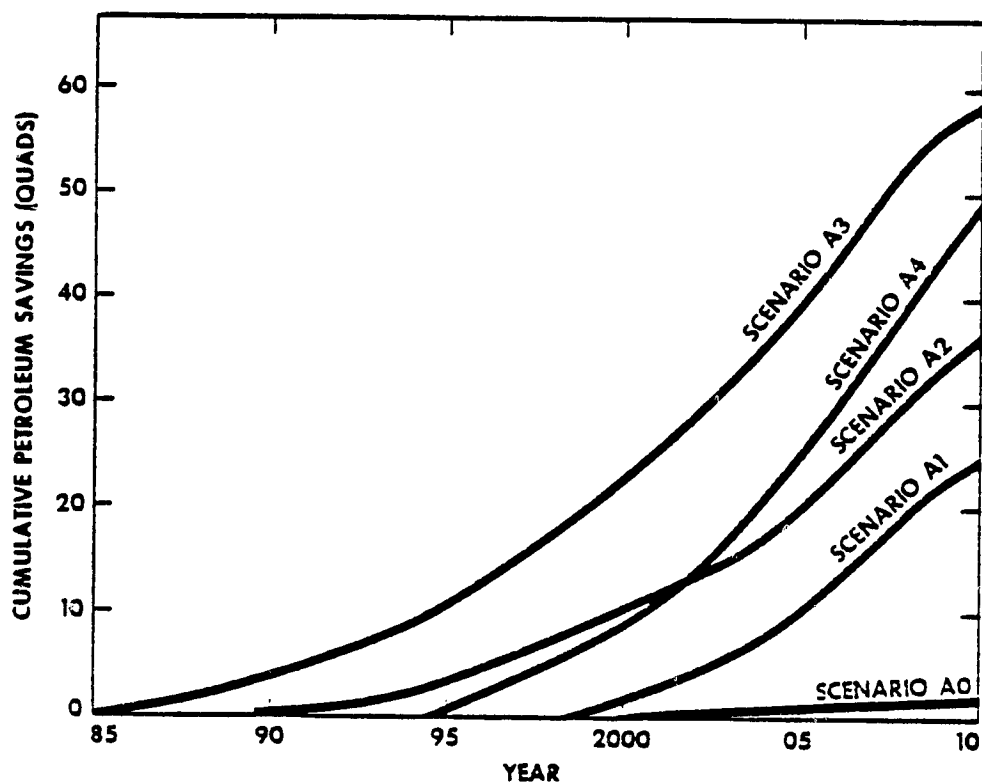


Figure 7-9. Cumulative Petroleum Savings with Hybrid Vehicles

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